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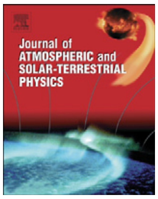

Forecasting the parameters of sunspot cycle 24 and beyond

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ABSTRACT

Solar variability is controlled by the internal dynamo which is a non-linear system. We develop a physical–statistical method for forecasting solar activity that takes into account the non-linear character of the solar dynamo. The method is based on the generally accepted mechanisms of the dynamo and on recently found systematic properties of the long-term solar variability. The amplitude modulation of the Schwabe cycle in dynamo's magnetic field components can be decomposed in an invariant transition level and three types of oscillations around it. The regularities that we observe in the behaviour of these oscillations during the last millennium enable us to forecast solar activity. We find that the system is presently undergoing a transition from the recent Grand Maximum to another regime. This transition started in 2000 and it is expected to end around the maximum of cycle 24, foreseen for 2014, with a maximum sunspot number $R_{\max} = 68 \pm 17$. At that time a period of lower solar activity will start. That period will be one of regular oscillations, as occurred between 1730 and 1923. The first of these oscillations may even turn out to be as strongly negative as around 1810, in which case a short Grand Minimum similar to the Dalton one might develop. This moderate-to-low-activity episode is expected to last for at least one Gleissberg cycle (60–100 years).

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1. Introduction

Presently existing methods for forecasting sunspot activity may be subdivided into three types (cf. Usoskin and Mursula, 2003): (a) statistical methods that consider inherent statistical properties of solar activity (e.g. Kane, 1999; Ogurtsov, 2005a, b), (b) physical methods, based on an assumed mechanism for the solar dynamo that yields links between the poloidal and the toroidal magnetic field components and that are further based on some precursor type parameters of solar activity (e.g. Schatten, 2005; Svalgaard et al., 2005), and (c) physical–statistical methods which are combinations of the approaches (a) and (b) (e.g. Hathaway and Wilson, 2006; Duhau, 2003).

All the three methods have been applied for forecasting solar activity. In spite of the fact that some of these forecasts are fairly sophisticated, published predictions of the maximum sunspot number ($R_{\max}$) for the coming cycle are disappointingly divergent (see, e.g. Usoskin and Mursula, 2003; Li et al., 2001). They range from very high, as in the last 50 years (Hathaway and Wilson, 2006; Dikpati et al., 2006; Charvàtovà, 2008), over intermediate $R_{\max}$ values (Schatten, 2002; Duhau, 2003; Le and Wang, 2003; de Meyer, 2003; Sello, 2003; Ogurtsov, 2004, 2005a, b; Svalgaard et al., 2005; Schatten, 2005; Kane, 2007; Aguirre et al., 2008) to very small $R_{\max}$ values (Badalyan et al., 2001; Komitov and Kaftan, 2003; Callebaut et al., 2003). These latter forecasts might lead to another Grand Minimum episode. These conflicting results of predictions may be due to the fact that most of the methods used to forecast solar activity (for reviews see, e.g. Hathaway et al., 1999; Schatten, 1998) assume the relation between the involved variables to be linear. However, the solar dynamo is a non-linear system with deterministic chaotic elements (Weiss, 1987; Feynman and Gabriel, 1990; Ostryakov and Usoskin, 1990; Kremliovsky, 1995; Usoskin and Mursula, 2003; Duhau, 2003; Weiss and Tobias, 2004; De Jager, 2005; Aguirre et al., 2008). Hence, the solar dynamo behaviour, as manifested in its temporal evolution, differs fundamentally from that assumed in most predictions in which the non-linearity was not considered. The divergence between presently existing methods to forecast sunspot activity calls for a further development of the prognosis technique.

The dynamo system in an axial-symmetric model has 4 degrees of freedom, i.e. the toroidal and poloidal magnetic field components and the meridional and azimuthal components of the velocity field (see, e.g. Knobloch et al., 1998; Durney, 2000; Dikpati et al., 2004). The geomagnetic index aa at minima, $aa_{\min}$ (Mayaud, 1972), and the sunspot number at maxima, $R_{\max}$, are measures of the amplitudes of the poloidal and toroidal magnetic components of the solar cycle, respectively (cf. Duhau, 2003 and references therein). The non-linear evolution of the dynamo system from 1844 to 2000 was shown by means of an $R_{\max}$ vs.

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$aa_{\min}$ phase diagram introduced by Duhau and Chen (2002). Their method was improved by Duhau and De Jager (2008) and applied by them to study the non-linear evolution of the solar dynamo during the last millennium, from proxy data of the sunspot numbers (Nagovitsyn, 1997, 2005, 2007) and the geomagnetic index *aa* (Nagovitsyn, 2006) time series. It was found that the dynamo system is characterized by an invariant, sharply defined, transition state around which the system states oscillate. The oscillations were decomposed in multidecadal and Gleissberg oscillations. The first (henceforth called 'decadal' for simplicity) is defined for the present purpose as the superposition of all wavelet components with periods in the 15–72 year band, where the lower limit is chosen such that the influence of the Schwabe cycle is eliminated from the resulting data. The Gleissberg oscillations are defined here as the superposition of all wavelet components with periods above 72 years, to which the linear trend is added and from which the transition level's coordinate is subtracted. This decomposition was made to facilitate solar activity predictions, since we (Duhau and De Jager, 2008) found that the decadal oscillation includes the odd–even rule and that the Gleissberg cycle is a succession of harmonic oscillations with a period in the Suess band (Great Episodes) and in the Gleissberg band (Regular Episodes). Moreover, we found evidence that solar variability is mainly time-correlated in the long-term (Gleissberg) time scale, hardly so in the decadal one. The method, developed here, belongs essentially to the above-described method (c) but is substantially improved by including the non-linear character of the solar dynamo.

The system appears to move sequentially towards the three types of quasi-periodic behaviours in brief phase transitions. The character of these transitions appears to depend on the distance of the path of the dynamo components in phase space to the transition point.

On the basis of this new information we study in this paper the forthcoming solar variability and in particular the nature of the next solar dynamo episode and the characteristics of solar cycle 24. This is done in Sections 2–4. In Section 5 we discuss the causes of the large dispersion in presently existing predictions of sunspot maximum #24. A summary of the results and our main conclusions are given in Section 6.

2. The Gleissberg cycle in solar variability and the forecast of the next dynamo episode

Outline: In this section we study the phase diagram of the Gleissberg cycle in the plane of the two magnetic field components for the forthcoming half century in order to forecast the behaviour of the solar dynamo for that period.

As mentioned in Section 1, the dynamo is characterized by a sharply defined transition state (coordinates: $R_{\max} = 93.38 \pm 0.69$ spot number units and $aa_{\min} = 10.34 \pm 0.08$ nT). There are three types of dynamo behaviour around the transition point: the Grand Minima (M), the Grand Maxima (H), and the Regular Oscillations (R). The first two last for half a strong oscillation, negative and positive respectively. These are periods of time in the upper part of Gleissberg band of periods. An example of a Grand Maximum is the 1923–2008 large loop; it is also shown in the second quadrant of the phase diagram of Fig. 1. The R-type oscillations are rather weaker and can last longer than the H and M episodes, viz. for time periods of 60–200 years, equivalent to one to a few Gleissberg cycles (cf. the loops from 1730 to 1923 in Fig. 1).

Between the various types of episodes there are brief phase transitions with different durations, roughly of the order of a Schwabe cycle. There are two types of such phase transitions. We called them C- and G-types. The G-type transitions occur when the values of the Gleissberg oscillations around the transition state, both in the poloidal and in the toroidal magnetic field components, differ simultaneously from zero by less than 0.1% of the transition point's coordinates. A G-type transition leads invariably to a Grand episode. If, however, one of the two components does not differ by less than 0.1% from the corresponding transition state coordinate a C-type transition occurs. Such a transition is always followed by an R-type episode.

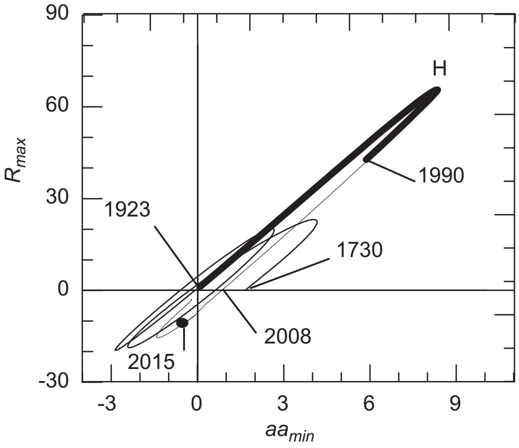

Fig. 1. The phase diagram ($R_{\max}$, $aa_{\min}$) for the Gleissberg cycle for the period 1730–1990 (cf. Fig. 6d in Duhau and De Jager, 2008) (full line) and its extrapolation to 2015 (dashed line). The two coordinates are proxies for the toroidal ($R_{\max}$) and the poloidal ($aa_{\min}$) components of the solar dynamo. Light lines in the diagram refer to counterclockwise motion and dark and dashed lines to clockwise motion.

The Gleissberg oscillation, as determined for the interval 1923–1990 (cf. Fig. 6 in Duhau and De Jager, 2008), is well represented by a sine function (cross-correlation coefficient 0.99). It appears that in 2008 (see Fig. 1) its value in $R_{\max}$ is zero to within a high degree of accuracy (0.0004 sunspot numbers) while $aa_{\min}$ was still deviating from zero by 0.84 nT, which is 8% of the relevant transition state coordinate. This fact implies that the current transition is of a C-type. Hence it will be followed by an R-type episode, during which the sense of motion of the path in the phase diagram is always equal to that of the previous Grand Episode.

A similar situation occurred at the end of the episode in the 12th century that we called H_{-2} (cf. Fig. 6a in Duhau and De Jager, 2008). In analogy with, and according to the rules that appear to govern the solar dynamo, we therefore expect that the forthcoming episode will be of the R-type and that its track in the phase diagram, after the past H-type episode, should be clockwise. Following our earlier designations we label the forthcoming episode R_{+1}.

To estimate the error in the predicted path beyond the year 2008 we extrapolate the forthcoming R_{+1} Gleissberg cycle in $R_{\max}$ by assuming it successively equal to the two extreme cases that occurred during the last millennium. One of these was the R_{-2} episode (from 1165 to 1230). It was the weakest episode of regular oscillations of the last millennium. The other is the R episode (1730–1923), which had the largest amplitude. We find that the differences between the two cases are not discernible before 2015 in the scale of Fig. 1. This is due to the fact that, as follows from an analysis of the proxies for the last millennium, the length of a Gleissberg cycle depends directly on its amplitude, where lengths of 60 and 95 years correspond with amplitudes of 15 and 25 sunspot number units, respectively. Hence, the strongest cycle is varying slower than the weakest (cf. also Fig. 4).

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