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The Forthcoming Grand Minimum of Solar Activity

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Abstract

We summarize recent findings about periodicities in the solar tachocline and their physical interpretation. These lead us to conclude that solar variability is presently entering into a long Grand Minimum, this being an episode of very low solar activity, not shorter than a century. A consequence is an improvement of our earlier forecast of the strength at maximum of the present Schwabe cycle (#24). The maximum will be late (2013.5), with a sunspot number as low as 55.

1. Introduction

Solar activity is believed to be associated with climate change (De Jager and Duhau, 2009; De Jager et al., 2010; Miyahara et al., 2010). Sunspot activity can be concentrated in the two solar hemispheres and they appear to fluctuate for 11 year cycles. However, prolonged episodes of reduced sunspot activity, such as the Maunder Minimum (named after solar astronomer Edward W. Maunder), were clearly linked with an episode of extreme cooling and bitingly cold winters in Europe and North America, known as the "little ice age."

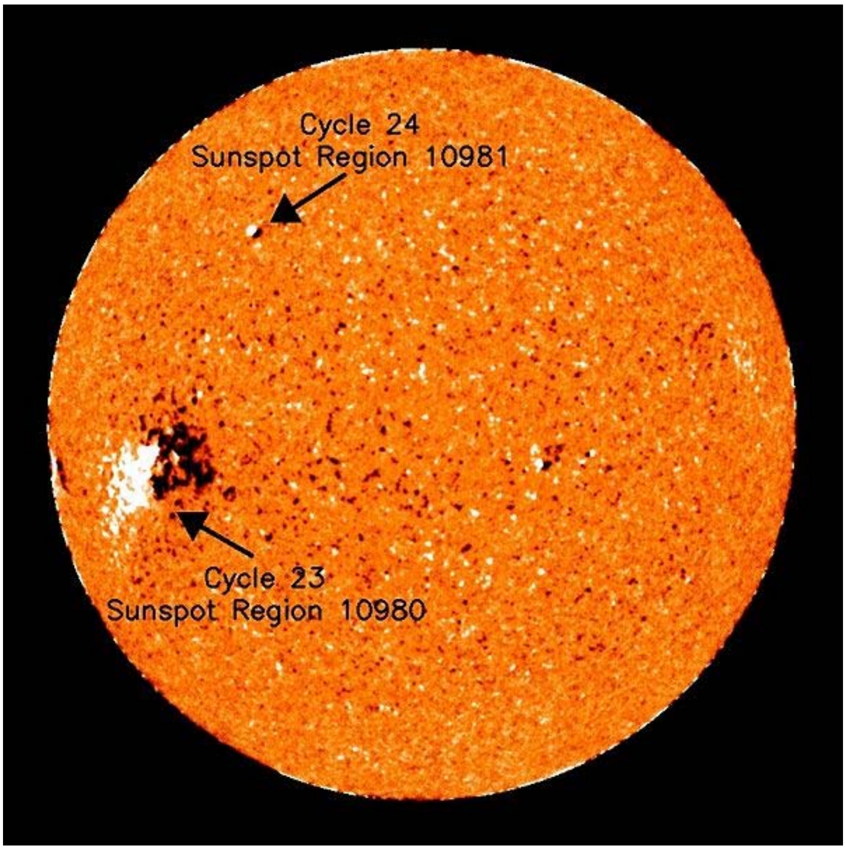

Figure 1. A sunspot of cycle 23 (equator) and first sunspot of cycle 24 (top). (January 4, 2008).

Predictions of the maximum sunspot number (R_{max}) for the forthcoming sunspot cycle 24 range from very high over intermediate to very small values (for review see De Jager and Duhau, 2009). Forecasts of the latter type may lead to another Grand Minimum episode (Miyahara et al., 2010). The conflicting predictions may be due to the possibility that at present the dynamo system is undergoing a chaotic transition from the Grand Maximum of the 20th century to another regime (Duhau, 2003; De Jager and Duhau, 2009).

Specifically, although its detailed mechanisms are unknown, the solar dynamo generates the Sun's magnetic field via a circular electric current flowing deep within the star. The solar plasma is a highly conductive medium. In the tachocline, about 200 000 km below the surface, in the presence of a seed field, currents are generated at levels where different latitudes of the sun rotate at different speeds, while interacting with deep-seated convective motions, thus amplifying strong magnetic fields (as specified by laws of magnetohydrodynamics). Like the sunspot cycle, the solar dynamo reverses itself every 11 years, and this triggers sunspot activity. It is believed that during the Maunder Minimum, the rotation of the sun may have slowed. Therefore, the future of sunspot behaviour depends to a large extent on the state of the dynamo during the transition (Lorentz, 1993).

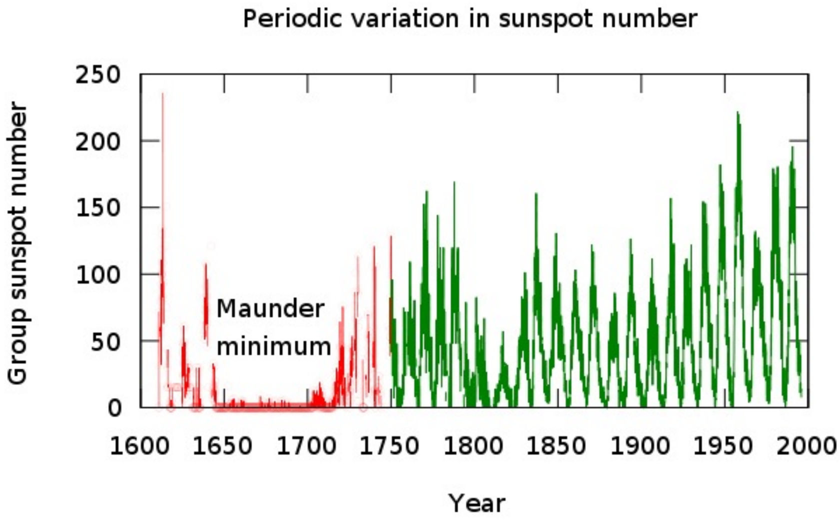

Figure 2. Variations in the sunspot activity depicting the Maunder Minimum.

A method for predicting the next Grand Episode, based on previous results on the modes of oscillations in the solar dynamo (summarized in De Jager and Duhau, 2010) was introduced by de Jager and Duhau (2009). One of the results was the recognition of a transition from the Grand Maximum of the 20th century to another Grand Episode. This transition period started in 2000 and is expected to end in 2013.

Based on the above mentioned methodology and by using new data for the geomagnetic aa index we foresee that a Grand Minimum is immanent. Thus, a prolonged period of relative global cooling is forecasted. The relevant mechanisms are described.

2. Solar Variability and the Phase Diagram.

Solar variability is dominated by the two main solar magnetic field components: the toroidal and poloidal magnetic field components of the tachocline, which is a layer, approximately 30000 km thick and situated about 200 000 km below the solar surface. Since these internal fields are not directly observable, while direct observations of the equatorial and polar fields are only known for a limited time interval, we need ‘proxies’ for these magnetic field components.

A proxy for the toroidal magnetic fieldstrength is $R_{max,}$ the maximum number of sunspots in successive Schwabe cycles (Nagovytshin, 2005); cf. Fig.3a. With regard to the poloidal field component it was suggested by Russell (1975), Russell and Mulligan (1995), and Duhau and Chen (2002), that a proxy for the maximum poloidal magnetic fieldstrength is $aa_{min,}$ the minimum value of the aa magnetic component. The aa data are based on simultaneous measurements of the terrestrial magnetic fieldstrength in Greenwich (UK) and Adelaide (Australia). The first series since 1868 (Mayaud, 1975) was extended down to 1844 (Nevanlinna and Kataja, 1993), while improved data since 1868 were provided by Lockwood (priv.com.), cf. Fig. 3b.

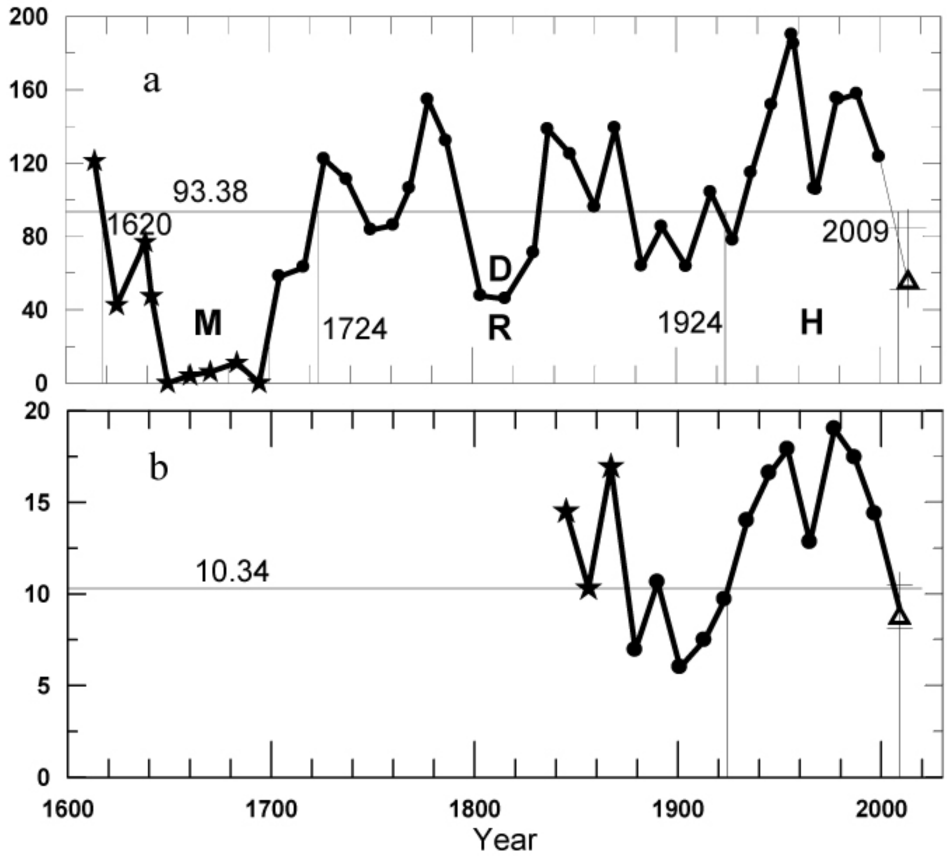

Fig. 3. Values of R_{max} since 1610 (a) and aa_{min} since 1844 (b). The R_{max} data from before and after 1705 are the Wolf and the Group Sunspot Numbers (Hoyt and Schatten, 1998) respectively, while the aa data are from Nevanlinna and Kataja (1993) and Lockwood (priv. comm.). The horizontal lines are the Transition point coordinates (see text). The crosses represent (a): the predicted values for sunspot cycle 24 maximum (67 ± 17) spotnumber and (b) the preceding geomagnetic index aamin (9.8 ± 1.2) nT (forecast by De Jager and Duhau, 2009), respectively, The triangles in (a) and (b) are the new predicted value of R_{max} for cycle 24 (see section 4) and the observed annual mean aa_{min} value centred in 2009.5 (8.7 nT), respectively . M, R and H refer to the types of Grand Episode occurring between the years indicated by the vertical lines. D refers to the Dalton Minimum.

For the study of the time history of the solar tachocline it makes sense to examine the simultaneous variation and the mutual dependence of the two proxies. To that end Duhau and Chen (2002) have introduced a phase diagram in which R_{max} is plotted as a function of aa_{min}. Its study gives rise to an interesting conclusion: it appears (Duhau and Chen, 2002; Duhau and De Jager, 2008) that at the time of transition from one Grand Episode to another the two proxies take well-defined values that we call the *'Transition Point'*. This point is found from the behaviour (see Figs. 3a and 4) of a long-period component, defined as the sum of the linear trend and the wavelet component periodicities in the upper Gleissberg and the Suess (de Vries) bands.

In Fig. 3a a full sequence is shown of the three types of Grand Episodes that alternated during the last millennium (Duhau and de Jager, 2008). These episodes are the Grand Minimum (M: 1620 – 1724), the Regular Oscillations (R: 1724 – 1924) and the Grand Maximum (H: 1924 – 2009). During these three periods R_{max} and aa_{min} were below, oscillating around, and above the transition point level, respectively. As seen in the phase diagram (Fig. 4) the long term variation is composed of a succession of closed ellipses around the transition point. We call this centennial cycle the 'Gleissberg cycle'.

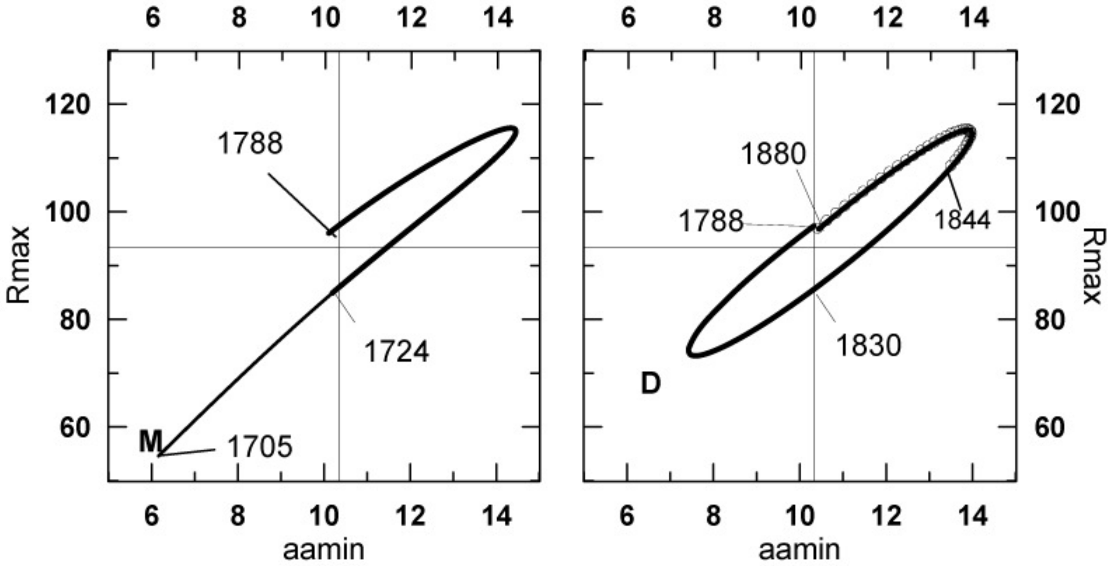

Figure 4. Phase diagram of the long term trend for the period 1705 to 1880. The vertical and horizontal lines cross the' transition point' (10.34, 93.38) coordinates. The thin line in the left diagram corresponds to the ascending branch of the Maunder Minimum. The thick lines in the two figures correspond to the 1724-1924 Regular Episode. The paths are always running counterclockwise. The aa_{min} data prior to 1844 are an extrapolation by Nagovitsyn (2006).

3. Solar Cycles; Physical Origin of the Periodicities beyond the Hale Cycle.

In solar variability there exist characteristic periodicities. Of these, the most important for the present investigation are defined as the Hale periodicity (17 – 32 years), the Lower Gleissberg (34 – 68 yrs), the Upper Gleissberg (72- 118 yrs) and the Suess (De Vries) (≈ 205 yrs) periodicities (for a review see De Jager, 2005). These ask for a physical interpretation. We note that the short Dalton type Minimum, occurring around 1810, does not appear in the Gleissberg cycle (see figure 4). This observation suggests that the Maunder and Dalton type minima have different physical origins.

Therefore, we proceed to a closer study of the solar periodicities and thereby wish to accentuate the difference between the character of periodicities in bound and open systems, in linear and non-linear systems. Specifying the differences is needed for a physical interpretation of the observations. Modes of oscillations of linear and stationary bound systems are harmonics functions; therefore any oscillation in these systems is well represented by the Fourier base function. The same is not true in non-linear systems with a non-stationary boundary for which the modes of oscillation change with time in frequency and in amplitude. For describing oscillations in such a kind of system a base function of compact support is needed. In the case of solar variability the important events are those in which the dominant periodicities change abruptly in time, which happens during a chaotic transition. This indicates that at the time of a transition an abrupt change in some boundary condition does occur. As a consequence the amplitude modulations of the sunspot cycle are a succession of 'quasi-harmonic episodes'. These are episodes during which the modulation of the sunspot cycle amplitude is a superposition of modes of oscillation that have highly variable amplitudes but nearly constant lengths. We call these oscillations 'quasi-harmonics'.

The amplitude modulation the Hale cycle can be split in a cycle and two quasi-harmonic modes. These are, the Gleissberg cycle, as defined in Section 2, a semi-secular oscillation and it first quasi-harmonic, the bi-decadal oscillation (see Fig. 5) , containing the time variables periodicities in the Lower Gleissberg and the Hale band, respectively. These modes may be linked to the symmetric and antisymmetric parts, with respect to the solar equator, of an identical phenomenon, probably the torsional oscillations in the tachocline. Actually, torsional oscillations in the convective layer have been observed in helioseismic data (for a review see Howe, 2009). Because of mass and angular momentum conservation they must be visible too in the meridional flux (see e. g. Shibahashi, 2006).

Allocating a physical interpretation to the – variable – Gleissberg cycle is more difficult but most probably this cycle is an inertial spin cycle, if it appears to find its basis in vibrations in inner core spin and the convective envelop (because of angular momentum conservation) in the inertial reference coordinates.

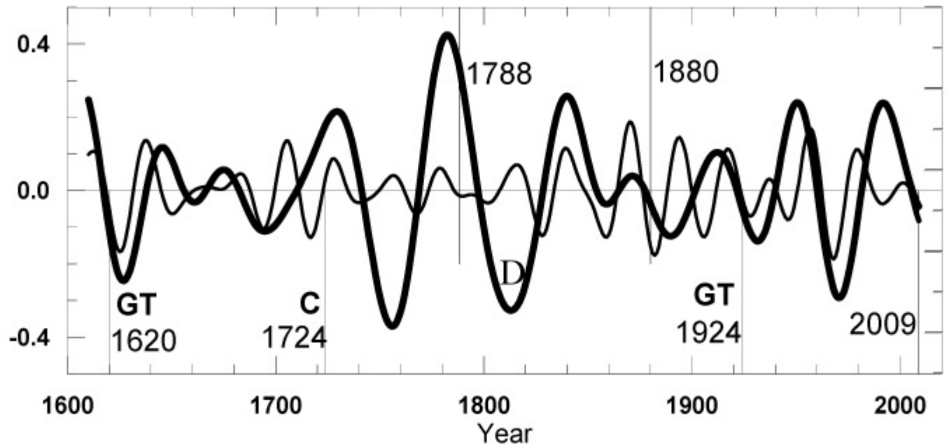

Figure 5: The symmetrical and anti-symmetrical parts of the torsional tachocline oscillations as seen in the semi-secular (thick line) and the bi-decadal (thin line) oscillations, respectively. They are found from the data of Fig. 5a. In 1620, 1788, 1880 and 1924 the path of the Gleissberg cycle in the phase diagram passed near to the origin (Duhau and De Jager, 2008) (examples are given in Fig. 3). In 1724 a sudden decreases of the amplitude of the Gleissberg cycle occurred at the start of a Regular Episode (cf. Figs. 3b and 6a).

In 1620 and 1924 the Gleissberg cycle passed close to the origin and simultaneously the semi-secular and the bi-decadal oscillations did so too. At these moments the Gleissberg cycle suddenly increased its length and amplitude, apparently related to the Grand Episodes of the M and the H type, respectively. To the contrary, in 1788 and 1880 the semi secular cycle was strong and positive. At these dates the Gleissberg cycle continued its weaker amplitude cycle, which is a characteristic of a Regular episode (cf. Figs 3b, 5, 6a).

In the framework of our suggested interpretation of the three solar dynamo modes we conclude that torsional oscillations stabilize the tachocline-convective layer system motions, leading to transfer of angular momentum in the latitudinal direction from the core spin to the tachocline.

The above suggestion leads us to conclude that, after a given transition, the amplitude and length of the Gleissberg cycle depend strongly on the phase of the torsional oscillations. This circumstance determines the apparent random evolution of the solar dynamo. However, solar dynamo evolution is determined by a regular sequence of three well defined quasi-harmonic episodes, separated by very brief chaotic transitions.

4. Forecasting the Next Grand Episode

Earlier, we (Duhau and De Jager, 2009) presented a forecast of solar activity during Schwabe cycle #24 that has just started. We foresaw a late (2013.5) and low (R_{max} = 67) solar maximum. This remarkably low solar activity gives rise to the question of the expected longer-term behaviour of the sun's activity. To answer it we make use of the diagnostic phase diagram as described in Section 2. As a correction to our earlier study (De Jager and Duhau, 2009) we have used the improved aa-data for deriving improved phase diagrams of the Gleissberg cycle. It is presented in Fig. 4 (left) and it shows a remarkable behaviour when compared to those for the earlier periods as the diagram shown in Fig. 4. It represents a perfect correlation between the long-term components of R_{max} and aa_{min}. We note that in the year 2009 the Gleissberg cycle exactly hit the origin. In our earlier study it was found that it missed it (see Fig. 1 in De Jager and Duhau, 2009) and so a Regular episode, starting with a short (about a half of a century), Dalton-type minimum was forecasted. The new data, though, lead to the prediction of a Grand Minimum. Strengthening this conclusion is the fact that both the semi-secular and the bi-decadal oscillations passed close to the origin in 2009 (Figs. 5 and 6b). Moreover, as happened during the transition of 1924, the semi secular cycle hit exactly the same point: (-0.045, 0.0) three years before the date of the corresponding transition (fig. 6 left).

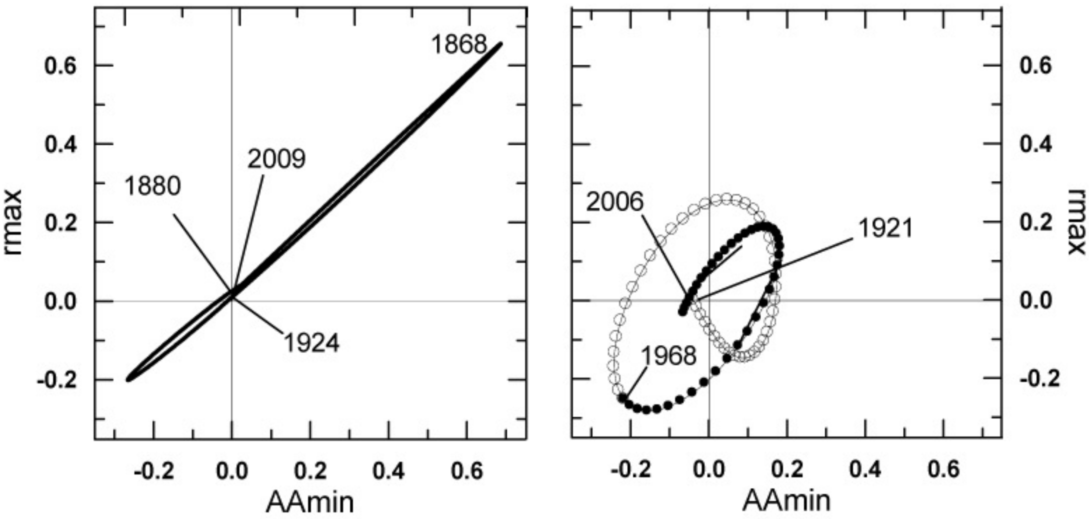

Fig. 6: The remarkable Gleissberg cycle phase diagram for the period 1880 to 2009 (left) and the semi-secular oscillation for the period 1921-2009 (right), as obtained from the new homogenised time series of the geomagnetic index aac (Lockwood et al. (priv. comm., 2009). The transition point coordinate values have been subtracted from the normalized data.

Support for the above conclusions about the immanence of a Grand Minimum is found in Makarov et al. (2010) who showed that the rest latitudes of the sunspot bands gradually tended to decrease during the past few decades (cf. Fig. 16 in De Jager and Duhau, 2010). That phenomenon was interpreted by the authors as an indication that a Grand Minimum could start around 2020 ~ 2030. The present situation may be compared with that around 1620, where the Maunder minimum was preceded by increasingly weaker Schwabe cycles (cf Fig. 2).

The fact that the symmetrical part of the torsional oscillations as seen in the semi secular oscillation (see figure 5) has still a appreciable polar component (– 0.045 nT) indicates that a seed field pointing southward is at the tachocline level during these transitions.

The magnitude of the sunspot maximum occurring at the end of a chaotic transition depends on the type of episode that develops after (De Jager and Duhau, 2009). After the 2009 transition an M-type instead of an R-type episode is expected to occur. Therefore the amplitude of the Gleissberg cycle will be nearly three times the one previously assumed. Therefore we expect that sunspot maximum #24 will even be weaker than the earlier prediction, with R_{max} = 55.

5. Summary and Conclusions

The dynamo system evolves over three kind of quasi-harmonic episodes separated by brief chaotic transitions. These episodes are well represented by a superposition of a cycle and two quasi-harmonic modes: the Gleissberg cycle, the semi-secular and its first quasi-harmonic, the bi-decadal oscillations, around the Transition State (Duhau and de Jager, 2008, De Jager and Duhau, 2009) A transition to a Grand (M or H) Episode occurs only when the three modes are passing simultaneously through the zero point. At that moment the tachocline-convective layer motions are going through a north/south symmetry. Evidence of this fact is provided by the observation of Mursula and Zeiger (2001) that the heliospheric magnetic field changed from northward to southward symmetry around 1930, which is at the time of ending of the 1924 transition.

Solar activity is presently going through a transition period (2000 – 2013). This will be followed by a remarkably low Schwabe cycle, which has started recently. In turn that cycle precludes a forthcoming Grand Minimum, most likely of the long type.

Flux transport dynamo models (for a review see Dikpati and Gilman, 2009) seem to contain all the necessary ingredients for realistic simulations of solar dynamo action. However, they predict a strong sunspot cycle 24 (Dikpati et al., 2006), comparable with those that occurred in the recent Grand Maximum. Observations instead indicate that this episode has ended (see De Jager and Duhau, 2010). These models assume a constant poloidal source at the tachocline-convective layer boundary. Our results indicate that the failure of that model is due to the fact that the boundary condition at the tachocline- convective layer boundary suddenly change during the transitions, a possibility that is not incorporated in the flux transport models.

This changing boundary conditions during the chaotic transitions is likely to be due to a sudden change of orientation of the tachocline-convective motions with respect to the relic field seated at the core. In fact, for starting the dynamo

loop, flux transport dynamo models need a seed field at the tachocline-convective layer boundary. Also, a relic field appears to be essentially necessary for having the radiative interior rotating as a rigid body and evidences indicating that his field is pointing southward have been provided since Cowling (1945) suggested its existence. (For a review see De Jager and Duhau, 2010; cf. also Mursula et al. 2001). The persistence of a negative polar field component at the transition state as found here, gives further support to these findings.

A further study of the physics underlying the excitation of the Gleissberg cycle and of the observed convective layer torsional oscillations (for a review see Howe, 2009) would be a relevant step in improving predictive models of solar activity.

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