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Reinforcing a Double Dynamo Model with Solar-Terrestrial Activity in the Past Three Millennia

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Abstract. By applying Principal Components Analysis (PCA) to solar magnetic synoptic maps in cycle 21-23 obtained with Wilcox Solar Observatory we derived analytical expressions for two principal components and their summary curve of solar magnetic field oscillations defined by dipole magnetic sources. In this paper we extrapolate backwards three millennia the summary curve describing solar activity and compare it with the relevant historic data. The extrapolated summary curve shows a remarkable resemblance to the sunspot and terrestrial activity reported in the past millennia: the Maunder Minimum (1645-1715), Wolf minimum (1200), Oort minimum (1010-1050), Homer minimum (800-900 BC), the medieval warm period (900-1200), the Roman warm period (400-10BC). We note that Sporer minimum (1460-1550) derived from the increased abundance of isotope Δ^{14}C is likely produced by a strong increase of galactic cosmic rays caused by a supernova Vela Junior occurred in the Southern hemisphere.

Keywords. solar activity, dynamo, geoactivity

1. Introduction

Our understanding of solar activity is tested by the accuracy of its prediction. The latter became very difficult to derive from the observed sunspot numbers and to fit sufficiently close into a few future 11 year cycles or even into a single cycle until it is well progressed (Pesnell 2008). The fact that a large number of model predictions for cycle 24 disagreed with the measured sunspot numbers suggests that the appearance of sunspots on the surface during a solar cycle is governed by the action of some physical processes of the solar dynamo that are not yet fully considered in the models.

In order to reduce dimensionality of these processes in the observational data, Zharkova *et al.* (2012) applied Principal Component Analysis (PCA) to the low-resolution full disk magnetograms captured by the Wilcox Solar Observatory in cycles 21-23. This approach revealed a set of 8+ eigen vectors of temporal variations of solar background magnetic field (SBMF), which seem to appear in pairs. These two principal components (PCs) reflecting the strongest waves of solar magnetic oscillations, are indicated by Zharkova *et al.* (2015) having the highest eigen values covering about 39% of the data variance, or a one $\sigma = 0.67$ interval.

The main pair of PCs is shown to be associated with the two magnetic waves attributed to the poloidal magnetic field produced by dipole magnetic sources (see Popova *et al.* 2013; Zharkova *et al.* 2015) describing a double dynamo action in two different layers

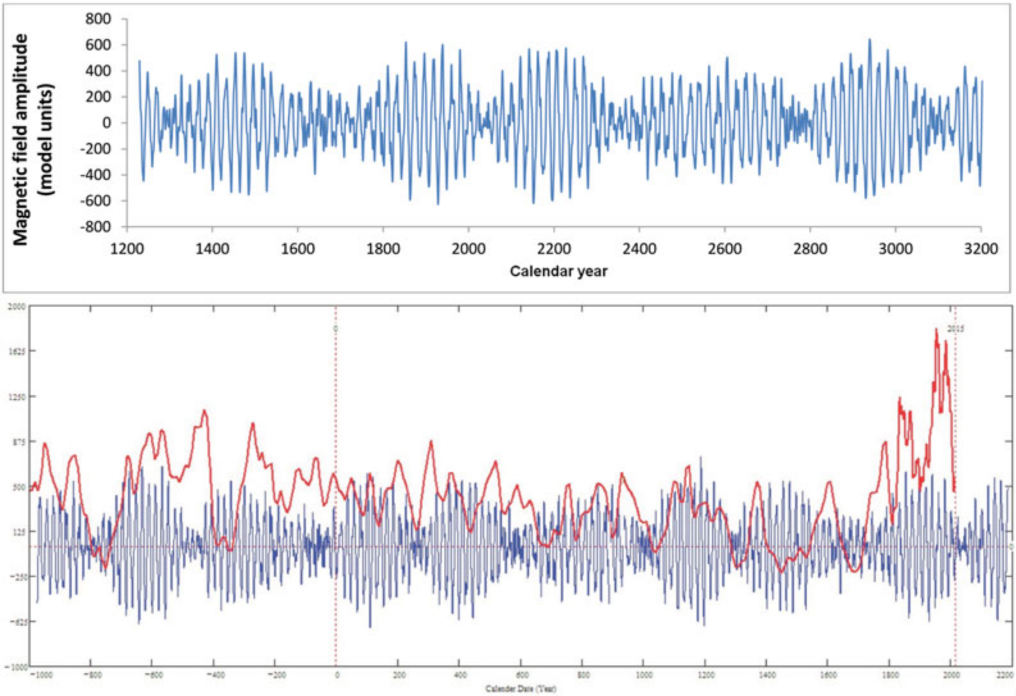

Figure 1. Top plot: the summary curve constructed using two Principal Components in arbitrary units (axis Y) for 1200AD to 3000AD, similar to Fig. 3 in Zharkova *et al.* (2015), with the removed horizontal pointers. The bottom plot: solar activity prediction backward 3000 years with a summary curve (blue line) of the two principal components (PCs) of solar background magnetic field (SBMF) (Zharkova *et al.* 2015, Zharkova *et al.* 2015) versus the reconstruction by Solanki and Krivova (2011) (red line) by merging the sunspot curve (17-21 centuries) and carbon dating curve (before the 17 century).

of the solar interior. These waves are found originating in the opposite hemispheres and travelling with an increasing phase shift to the Northern hemisphere (in odd cycles) and the Southern hemisphere (in even cycles) (Zharkova *et al.* 2012, 2015). The maximum (or double maximum for the double waves with a larger phase shift) of solar activity for a given solar cycle coincides with the time when each of the waves approaches their maximal amplitudes. The hemisphere where it happens becomes the most active one. This can naturally account for the north-south asymmetry of solar activity often reported in many cycles. The resulting summary curve if these two PCs describe the resulting solar activity shown by Shepherd *et al.* (2014).

The existence of two waves in the poloidal (and toroidal) magnetic fields instead of a single one for each of them, used in most prediction models, and the presence of a variable phase difference between the waves was shown by Zharkova *et al.* (2015) to naturally explain the difficulties in predicting sunspot activity with a single dynamo wave on a scale longer than one solar cycle as noted by by Karak and Nandy (2012). In support of this statement Shepherd *et al.* (2014) showed that the sunspot activity is associated with the modulus summary curve, which is a derivative from the two waves generated in two layers of the solar interior and not from a single layer accepted by most models.

In the current paper we expand the summary curve to the past three thousand years using findings from Zharkova *et al.* (2015) and compare this curve with the recent longterm reconstruction of stochastic solar activity suggested by Solanki and Krivova (2011) and Usoskin (2013).

2. Solar activity in the past three millennia with the summary curve

Findings by Zharkova *et al.* (2015) reveal very stable magnitudes of the two principal eigen values for each and every solar cycle considered, whether they derived from a single cycle, or a pair of cycles in any combination, or all three of them (21-23) (see Figure 1, top plot). This proves that the parameters of own oscillations of the Sun are maintained the same over a large period of time re-assuring a very good health of the Sun's heartbeat, or the solar dynamo. We have shown that visible variations of the wave parameters occur owing to different conditions in these two layers, so that the waves are generated with close but not equal frequencies. These variations are shown to cause a beating effect of these two magnetic waves, which produces an envelope grand cycle with the grand minima regularly occurring every 350-400 years.

Now we extend this extrapolation backwards to 3000 years (to 1000 BC) as shown in Figure 1 (bottom plot, blue curve). For comparison, we have overplotted the curve of the supposed solar activity derived by Usoskin (2013); Solanki and Krivova (2011) (red curve), which used sunspot numbers until 17 century and the isotope Δ^{14}C abundances prior to the 17 century.

It can be noted that our summary curve in Figure 1 reveals a remarkable resemblance to the sunspot and terrestrial activity reported in the past centuries showing accurately the recent grand minimum (Maunder Minimum) (1645-1715), the other grand minima: Wolf minimum (1300-1350), Oort minimum (1000-1050), Homer minimum (800-900 BC); also the Medieval Warm Period (900-1200), the Roman Warm Period (400-150 BC) and so on. These minima and maxima reveal the presence of a grand cycle in solar activity with a duration of about 350-400 years, with the next grand cycle minimum (Modern minimum) approaching in 2020-2055 as reported by Zharkova *et al.* (2015).

It turns out that longer grand cycles have a larger number of regular 22 year cycles inside the envelope of a grand cycle but their amplitudes are lower than in shorter grand cycles. This means that there are significant modulations of the magnetic wave frequencies generated for different grand cycles in these two layers: a deeper layer close to the bottom of the Solar Convective Zone (SCZ) and shallow layer close to the solar surface whose physical conditions derive the dynamo wave frequencies and amplitudes. The larger the difference between these frequencies the smaller the number of regular 22 years cycles and the higher their amplitudes.

In addition, to a grand cycle of 350-400 years, one can also derive a larger super-grand cycle of about 1900-2000 years by combining the curves in Figure 1 (bottom plot, blue curve) and the curve used for the prediction for the next 1000 years in Fig. 3 of Zharkova *et al.* (2015) reproduced here in Figure 1 (top plot). This super-grand cycle can be distinguished by comparing the five grand cycles in Figure 1 (top plot) (years 1001-3000 AD) with the next 5 grand cycles restored for 1000 BC-1000 AD) (bottom plot), which clearly show the repeating patterns for every 5 grand cycles.

It has to be noted that so far we only used the two PCs of the solar magnetic field oscillations assigned by Zharkova *et al.* (2015) to dynamo waves produced by dipole magnetic sources. Popova *et al.* (2017) shown that consideration of the next pair of magnetic waves produced by quadruple magnetic sources allows us to recover Dalton minimum (1790-1820) and another centennial cycles (caused by Gleissberg cycle).

However, Sporer minimum (1460-1550) is not present in our summary curve (the blue curve) plotted in Figure 1, showing instead during the same period of time a maximum

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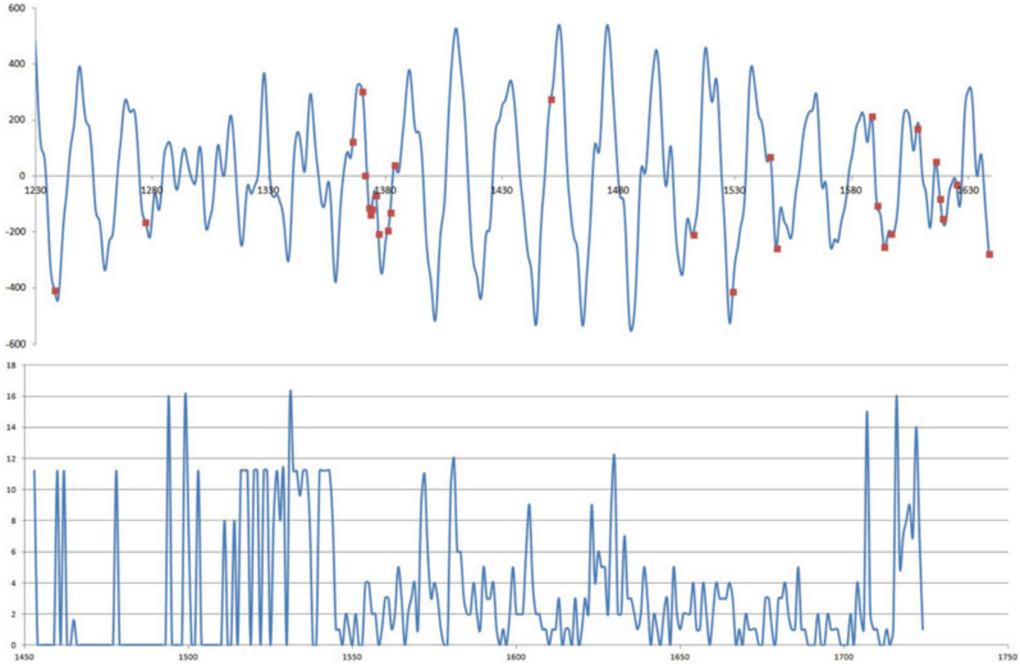

Figure 2. Top plot: verification of the summary curve (blue line) with large sunspots (red dots) placed at the time of their observations from the pre-telescope visual observations in Sporer minimum (1450-1550) from Wittman (1978); Wittman and Xu (1987). Note, that red dots for large sunspot were placed onto the activity curve at the exact times of their occurences during Sporer minimum. Bottom plot: distributions of terrestrial auroras over the period of Sporer minimum revealing the strongest auroras ever observed (from Schlamminger (1990); Schroder and Treder (1999)).

of the grand cycle previous to the modern one (17-21 centuries). We discussed this discrepancy in Zharkova *et al.* (2017) uncovering some important properties of the solar activity caused by quadruple magnetic sources. For the particular grand cycle including Sporer minimum the solar activty curve was surprisingly well verified by the naked eye observations of sunspots (see Figure 2, top plot).

Moreover, the intensities of auroras during the period of Sporer minimum are much higher than in any periods of maximal solar activity in the past. In fact, the aurora intensities in this period significantly exceed the intensities of auroras ever observed on Earth in the past 500 years (see Figure 2, bottom plot).

Keeping in mind that, normally, a) strong auroras coincide with the maxima of solar activity and not with its minima, and b) in the telescope era such strong auroras, as they were seen in the 14-16 centuries were never observed as indicated by Figure 2 (bottom plot), it is logical to assume that in that period there were some other sources, which increased a flow of relativistic particles causing these auroras. The Sun could not provide such the increase as its grand period for these centuries was not much different from the previous and the following grand cycles as shown in Figure 1.

Hence, we need to look at contributions of extra-terrestrial effects, e.g of supernovae, which were somehow overlooked despite supernova remnants are the major sources of galactic cosmic rays. There were a number of supernovae recorded in the past centuries which could affect the Earth as shown by Zharkova *et al.* (2017). Remnants of the mysterious supernova Vela Junior, which exploded in 1290 and became a neutron star, was found in 1998 located in the southern sky in the constellation Vela only 650-700 light-years away, which could cause the terrestrial effects during 13-15 centuries.

This supernova, at 46 degrees south, may have been too far south for observers in the Northern hemisphere to notice it, especially if it obtained peak brightness during the northern summer. At this declination, the supernova would be invisible above about 45 degrees north, making it invisible to the majority of Europe. This is the supernova, which could be the source of strong cosmic rays occurred in 13-15 centuries leading to large terrestrial auroras, and as consequence, to a long streak of epidemics in the southern countries on Earth, including China (see Reischauer *et al.* 1960).

3. Conclusions

Given a number of grand minima and grand maxima correctly fit by the summary curve combined with other means of the curve verification discussed above, we can confidently reinforce our previous findings (Zharkova *et al.* 2015) that the basic features of the solar activity are well reproduced by the two magnetic waves generated by dipole magnetic sources in two different layers of the solar interior. This finding also emphasizes the fact that the solar activity has a very well-maintained periodicity of these waves maintained over millennia reflecting a very good dynamo-health of the Sun.

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