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Reinforcing the double dynamo model with solar-terrestial acitivity 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 predict the upcoming Modern grand minimum to occur in 2020-2055, which will have higher solar activity and shorter duration compared to the previous grand minimum, the Maunder Minimum. 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 Vella Junior occurred in the high Southern skies.

Keywords. solar activity, dynamo, geoactivity

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1. Introduction

Cycles of magnetic activity are associated with the action of a mean solar dynamo mechanism called '$\alpha - \Omega$ dynamo' by Parker (1955) assuming that the action of the solar dynamo occurs in a single spherical shell, where twisting of the magnetic field lines (α-effect) and the magnetic field line stretching and wrapping around different parts of the Sun, owing to its differential rotation (Ω-effect), are acting together (see Jones et al. (2010) and references therein). As a result, the magnetic flux tubes (toroidal magnetic field) seen as sunspots are produced from the solar background magnetic field (SBMF) (poloidal magnetic field) during 11 years of solar cycle by a joint action of differential rotation and radial shear, while the conversion of toroidal magnetic field into poloidal field is governed by the convection in a rotating body of the Sun. The action of the Coriolis force on the expanding, rising (compressed, sinking) vortices results in a predominance of right-handed vortices in the Northern hemisphere and left-handed vortices in the Southern hemisphere leading to the equatorward migration of sunspots visible as butterfly diagams during a solar cycle duration.

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)). Consistent disagreement in a large number of models between the measured sunspot numbers and the predicted ones for cycle 24 is likely to confirm that the appearance of sunspots on the surface during a solar cycle is governed by the action of some physical processes of solar dynamo, which are not yet considered in the models.

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

The main pair of PCs is shown to be associated with the two magnetic waves attributed to the poloidal magnetic field (see Popova et al. (2013), Zharkova et al. (2015)) describing a double dynamo action in two differentl layers of the solar interior with dipolar magnetic sources. 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), Zharkova et al. (2015)). The maximum (or double maximum for the double waves with a larger phase shift) of solar activity for a given cycle coincides with the time when each of the waves approaches a maximum amplitude and 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.

At every phase of an 11 solar cycle, these two magnetic waves of poloidal field can be converted by electromotive force to a toroidal magnetic field associated with sunspots (Parker (1955), Popova et al. (2013)). The existence of two waves in the poloidal (and toroidal) magnetic fields instead of a single one for each of them, used in the most prediction models, and the presence of a variable phase difference between the waves was shown by Karak and Nandy (2012) to naturally explain the difficulties in predicting sunspot activity with a single dynamo wave on a scale longer than one solar cycle. In support of this statement Shepherd etal. (2014) showed that the sunspot activity is associated with the modulus summary curve, which is a derivative from these two wave summary curve and not from a single one.

However, the prediction of solar activity for the two millennia reported in Zharkova et al. (2015) has been challenged by Usoskin (2017), who claims the solar activity to be a stochastic process, which cannot be derived correctly from a magnetic field for just three solar cycles and can be reconstructed only by Artificial Intelligence methods.These points are clearly answered in our recent paper by Zharkova et al. (2017). Here we prove again the sun has a stable heartbeat by applying our findings of Zharkova et al. (2015) for the past three thousand years and by comparing them with the recent long-term reconstruction of the stochastic solar activity suggested by Solanki and Krivova (2011), Usoskin (2013) based on the carbon 14 isotope time dating.

Moreover, we show that Sporer minimum is an artefact of the terrestrial and Galactic activity with powerfull supernova occurred in close vicinity and is unlikely to be associated with solar activity at all. This reinforces our previous finding of solar activity coming from the two magnetic waves, or PCs, generated by a double solar dynamo as derived from the full disk magnetograms in cycles 21-23 and proves that solar activity has the very well-maintained periodicity over multiple millennia.

2. Restoration of the double dynamo waves for the past three millennia

Zharkova et al. (2015) tested with Principal Component Analysis the original magnetic field data from full disk magnetograms for the past 3 solar cycles (21-23) and derived the eigen values and eigen vectors of solar oscillations. These came in pairs with the highest eigen values assigned to the two principal components (PCs) associated with a dipole magnetic source. These waves can be closely reproduced in Zharkova et al. (2015) by the simulated waves derived from the two layer dynamo model with meridional circulation similar to the two cells reported from helioseismic observations by Zhao et al. (2013). Hence, Zharkova et al. (2015) called these PCs the double dynamo waves.

Findings by Zharkova et al. (2015) reveal very stable magnitudes of eigen values rel toevant these two dynamo waves 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). 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 heart, or the solar dynamo. The variations of the wave parameters occur owing to different conditions in these two layers where the waves are generated with close but not equal frequencies. These variations are shown to cause the beating effect of these two waves which produces a number of grand cycles of 350-400 years with the grand minima regularly occurring between them.

In the current paper we extend this extrapolation backwards to 3000 years to 1000 BC as shown in Fig.1 (top plot, blue curve). For comparison, we have overplotted the curve of the supposed solar activity prior 17 century derived from the isotope Δ^{14}C abundances by SolankiUsoskin (2013), Solanki and Krivova (2011) (top plot, red curve), which in the 17 century was merged with the curve derived from the sunspot numbers.

It can be noted that our summary curve extended to 3000 years in Fig. 1 reveals a remarkable resemblance to the sunspot and terrestrial activity reported in the past years from the carbon and berillium isotope datingSolanki and Krivova (2011) 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. We can also note that Dalton minimum (17901820) is appoximately present as it does show a reduced activity compared to the previous cycles, although it is not as strong as it was in the Maunder Minimum requiring possible a consideration of another 6 PCs (for quadruple magnetic sources) derived with PCA (see paper by PopovaPopova et al. (2013) and references therein).

These minima and maxima reveal the presence of a grand cycle in solar activity with duration of about 350-400 years, with the next grand cycle minimum (Modern minimum) approaching in 2020-2055 as reported by Zharkova et alZharkova et al. (2015). However, Sporer minimum (1460-1550) is not present in our summary curve (the blue curve) plotted in Fig.1, showing instead during the same period of time a maximum of the grand cycle previous to the modern one (17-21 centuries). We discussed this discrepancy in Zharkova et al. (2017) replying to comments by Usoskin (2017) uncovering some important properties of the solar-terrestrial and extra-terrestrial connections.

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 Fig.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 Fig. 1 (top plot). This super-grand cycle can be distinguished by comparing the five grand cycles in Fig. 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. Evidently, these cycles provide the important information about physical conditions in the two layers of the solar interior, which govern the variations of frequencies and amplitudes of the waves with a double beating effect, in order to reproduce the grand and super-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, while there are other 3 sets of the significant independent magnetic field components, which are associated with quadruple magnetic sources in these layersPopova et al. (2013). However, in the temporal variations of the summary curve we did not yet consider the waves produced by the quadruple magnetic sources, which are shown by Popova et al. (2017) to modify the individual variations of 22 year cycles within each grand cycle recovering Dalton and other centennial minima, or Gleissberg cycle, of magnetic activity.

The summary curve for the medieval period was verified with the pre-telescope observations of large sunspots observed (when possible) with the naked eye by Chinese and Japanese astronomers in the 13-16 centuries**?**, **?**, **?** presented in Fig. cr from Zharkova et al. (2017). Also it was found that in 14-16 centuries there were very strong auroras reported all over the skies over the whole Europe including Germany, Poland, Switzerland and even Portugal and other Mediterrenian countries **?**, **?**. For this particular grand cycle in Fig.**??** (bottom plot) we present the intensities of auroras during the period of Sporer minimum. Normally, strong auroras coincide with the *maxima* of solar activity and not with its minima and, especially, not with the prolonged minimum as Sporer's one is alleged. It is clear that the intensities of these unusual auroras significantly exceed the intensities of auroras ever observed on Earth in the past 500 years**?** and definitelly, they do not have lower intensities expected for a grand solar minimum if it existed in the 14-15 centuries.

3. The butterfly diagrams for Maunder and Modern grand minima

The third independent verifiction of this model comes from the comparison of the butterfly diagams simulated for the past Maunder minimum of the 17th century and plotted in Fig.**??** (top plot) with the observed butterfly diagram**?** plotted in Fig.**??** (bottom plot). It can be seen that the model butterfly diagrams between the two grand cycles about the Maunder minimum fits reasonably well the observed timing and locations of sunspots**?** showing much lower numbers of sunspots clustered about some times.

Here we also simulated the butterfly diagrams for the period of 2000 years with five grand cyclesZharkova et al. (2015) corresponding to the bottom curve Fig. 1 as derived from two magnetic waves of the solar poloidal field, generated by solar dynamo in two different layers with the modified Parker's non-linear two layers dynamo model with meridional circulation in the layers (see Methods section for the model descriptionZharkova et al. (2015)).

The simulation results of butterfly diagrams for the toroidal magnetic field are plotted for the upcoming (Modern) grand minimum in Fig.**??** (bottom plot) calculated using the dynamo equations from Popova et al.Popova et al. (2013) with the additionsZharkova et al. (2015). It is clear that the upcoming Modern minimum in 21st century is much smaller and will have more sunspots in cycles 25-27, compared to the Maunder Minimum in the 17 century.

4. Solar activity during Sporer minimum and possible effects of supernovae

One can note that Sporer minimum (14501540) indicated by Eddy**?**, Solanki and Krivova (2011) is not present in our summary curve plotted in Fig. 1 as indicated by Usoskin and Koval'stov **?** showing instead a maximum of the grand cycle during the same period of time. Moreover, after investigating the method of the time dating with $\Delta^{14}C$ isotope**?**, **?** and considering the terrestrial and extra-terrestrial conditions reported in the literature**?**, **?**, **?**, **?**, we have to question a validity of assigning the abundances of $\Delta^{14}C$ to the minimum of solar activity in the period of alleged Sporer minimum.

If one assumes that, indeed, it was a long Sporer minimum in solar activity in the 14-16 centuries, as suggested by the holocene curve derived from restoration of the carbon 14 isotope abundances **?**, Solanki and Krivova (2011), Usoskin (2013), then this minimum is in a very strong contradiction not only to our prediction in Fig. 1 but also to the other proxies of solar activity discussed in the section above, like large sunspots and strongest auroras ever observed on the Earth so far.

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, it is logical to assume that in that period there was/were some other source/sources, which increased a flow of relativistic particles causing the 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 (which we are experiencing now) as shown in Fig. 1.

While variations of the terrestrial magnetic field and solar activity were actively considered in the past Solanki and Krivova (2011), Usoskin (2013), the contributions of some other effects including the effects of supernovae were somehow overlooked. Possible implications of supernovae on the terrestrial events and carbon dating prior and during the Sporer minimum is discussed in the section below.

5. Near-Earth supernova effects on the terrestrial conditions in the 13-15 centuries

Supernova remnants are considered the major source of galactic cosmic rays as suggested by Walter Baade and Fritz Zwicky **?**. The streams of galactic cosmic rays caused by the supernovae are likely to increase very dramatically the backround cosmic ray intensity in the solar system and the Earth**?**, **?**, **?**, **?**, **?** that, in turn, can significantly affect an accuracy of the time dating with carbon 14 isotope during this period as pointed by a few authors**?** including Libby**?** who introduced this method.

The remnant of a mysterious supernova Vela Junior, which became a neutron star, was found in 1998**?** when gamma ray emissions from the decay of 44Ti nuclei were discovered. The remnant is located in the southern sky in the constellation Vela inside the much older Vela Supernova Remnant. The distance to this object is argued to be only 650-700 light-years away. Also it's radiation and particles reached the Earth comparatively recently, perhaps within the last 800 years, at about 1250-1290 as shown in Fig. 2.

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. And this is the supernova, which could be the major reason of a long streak of epidemics in the Earth, including China, in 14-15 centuries leading to decline in number of solar observers reporting large sunspots in the pre-telecope era.

6. Conclusions

In this paper we reproduce the summary curve for the last 3000 years and show it's remarkable resemblance to the sunspot and terrestrial activity reported in the past millennia including the significant grand minima: Maunder Minimum (1645-1715), Wolf minimum (1200), Oort minimum (1010-1050), Homer minimum (800-900 BC) combined with the grand maxima: the medieval warm period (900-1200), the Roman warm period (400-10BC) and so on. We also verify the extrapolated summary curve, as a solar activity curve, by the available pre-telescope observations of large sunspots, by the intense terrestrial auroras seen in 14-16 centuries and by simulated and observed batterfly diagrams for the Maunder Minimum. We predic the upcoming Modern grand minimum in 2020-2055, which will have sunspot activity slightly higher and duration twice shorter compared to the Maunder minimum in the 17 century.

We argued in Zharkova et al. (2017) that Sporer minimum (1460-1550) derived from the isotope Δ^{14}C time dating technique is likely produced by a strong increase of the terrestrial background radiation caused by the galactic cosmic rays of powerful supernovae. The supernova Vela Junior occurred close to the Earth (<700 light-years) could strongly affect its atmosphere leading to a long time of epidemics recorded in the Northern hemisphere, in general, and in China, in particular. These epidemics of deseases in the 15-16 century's China combined with Mongolian invasion and expansion of the Great Chinese Wall, eliminated the pool of people trained to observe sunspots until the 17 century.

Given the number of grand minima and grand maxima correctly fit, combined with the other means of verification discussed above, we can confidently reinforce our previous findingsZharkova et al. (2015) that the solar activity is produced by the two magnetic waves, or PCs, generated by a double solar dynamo as derived from the full disk magnetograms in cycles 21-23. This finding also emphasizes the fact that the solar activity has a very well-maintained periodicity of these dynamo waves maintained aver millennia that reflects a good dynamo-health of the Sun.

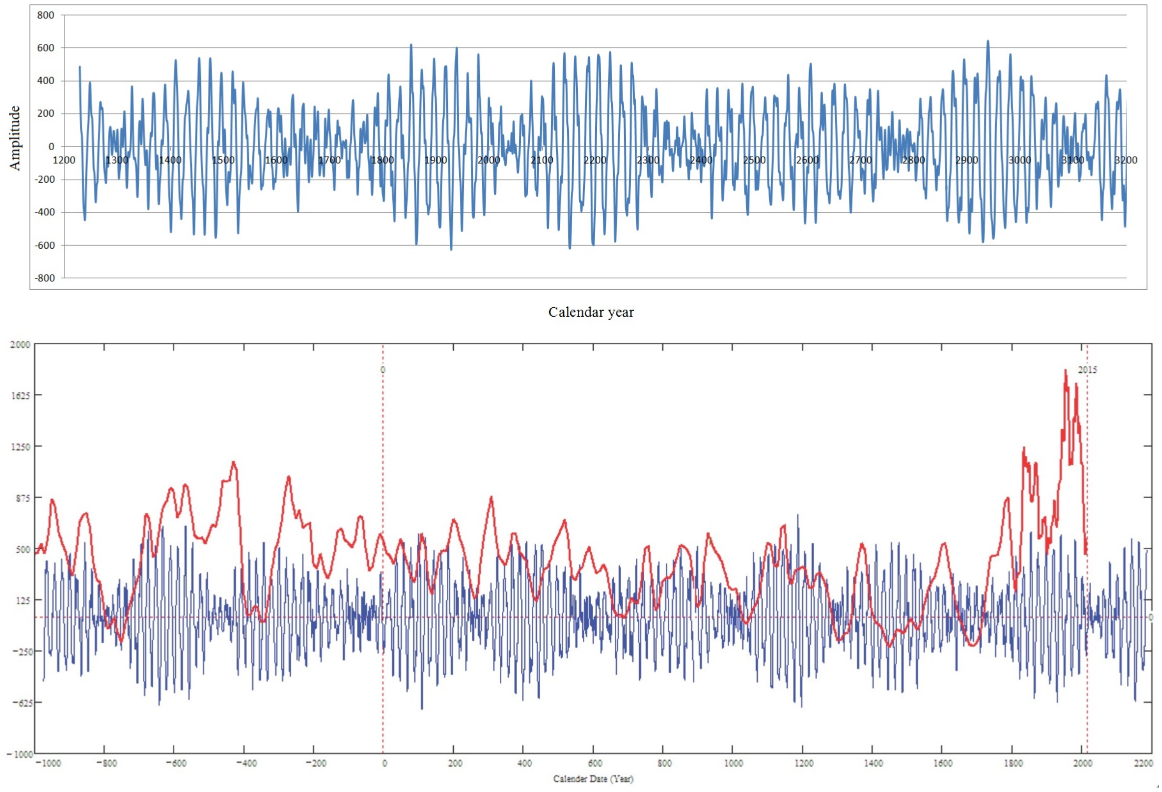

Figure 1. Top plot: the summary curve of two PCs calculated for 1200-3200 years, similarly to Fig. 3 in Zharkova et al. (2015), with the removed horizontal pointers. The bottom plot: solar activity prediction backward 3000 years with a summary curve (blue line) of the two principal components (PCs) of solar background magnetic field (SBMF)Zharkova et al. (2015) versus the reconstruction by Solanki et al.Solanki and Krivova (2011) (red line) by merging the sunspot curve (17-21 centuries) and carbon dating curve (before the 17 century).

References

Jones, C. A., Thompson, M. J. & Tobias, S. M., 2010 *S*pace Science Rev., 152, 591

Karak, B. B. & Nandy, D., 2012, *A*strophys. J. Lett. , 761, L13.

Parker, E. N. 1955, *A*strophys. J., 122, 293

Pesnell, W. D., 2008, *S*olar Phys., 252, 209

Popova, E., Zharkova, V. & Zharkov, S., 2013, *A*nnales Geophysicae, 31, 2023

Popova, E., Zharkova, V., Shepherd, S.J. & Zharkov, S., 2017, *J*ASTP,https://doi.org/10.1016/j.jastp.2017.05.006.

Shepherd, S. J., Zharkov, S. I. & Zharkova, V. V., 2014, *A*strophys. J., 795, 46.

Solanki, S. K. & Krivova, N. A., 2011, *S*cience, 334, 916.

Usoskin, I. G., 2013, *L*iving Reviews in Solar Physics, 10.

Usoskin, I., 2017, *J*ASTP, in press.

Zhao, J., Bogart, R. S., Kosovichev, A. G., Duvall, T. L., Jr. & Hartlep, T., 2013, *A*strophys. J.Lett., 774, L29.

Zharkova, V. V., Shepherd, S. J. & Zharkov, S. I., 2012, *M*NRAS, 424, 2943

Zharkova, V. V., Shepherd, S. J., Popova, E. & Zharkov, S. I., 2015, *N*ature Scientific Reports, 5, 15689

Zharkova, V. V., Popova, E., Shepherd, S. J. & Zharkov, S. I., 2015, *J*ASTP, in press.

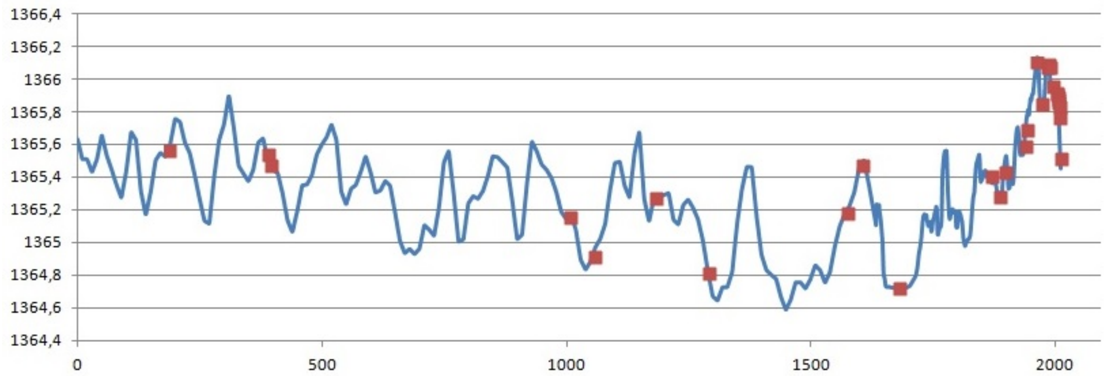

Figure 2. The solar activity curve (blue line) from Fig. 1 predicted by Usoskin et al.Solanki and Krivova (2011), Usoskin (2013) using carbon 14 dating technique for the period from 0 to 2010 AD with occurrences of supernovae marked by the red dots.