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Probing the Double Dynamo Model with Solar-Terrestrial Activity in the Past Millennia

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Abstract
Using a summary curve of two eigen vectors of solar magnetic field oscillations derived with Principal Components Analysis (PCA) from synoptic maps for solar cycles 21-24 we extrapolate solar activity backwards three millennia showing 9 grand cycles of 350-400 years. The summary curve shows a remarkable resemblance to the past sunspot and terrestrial activity: grand minima - Maunder Minimum (1645-1715AD), Wolf minimum (1280-1350 AD), Oort minimum (1010-1050 AD) and Homer minimum (800-900 BC) and grand maxima - modern warm period (1990-2015), medieval warm period (900-1200 AD), Roman warm period (400-10 BC) and others. We verify the extrapolated activity curve by pre-telescope observations of large sunspots, by maximum of the terrestrial temperature and extremely intense terrestrial auroras seen in 14-16 centuries and observed and simulated butterfly diagram for the Maunder Minimum (MM). We confirm the occurrence of upcoming Modern grand minimum in 2020-2055 and show it will have higher solar activity and shorter duration compared to MM. We argue that Sporer minimum (1450-1550) derived from the increased abundances of isotopes ^{14}C and ^{10}Be is likely produced by a strong increase of the terrestrial background radiation caused by galactic cosmic rays of powerful supernovae.

Introduction

Cycles of magnetic activity are associated with the action of a mean solar dynamo mechanism called '$\alpha - \Omega$ dynamo (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 (Brandenburg & Subramanian 2005; Jones et al. 2010). 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.

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 (Zharkova et al, 2012) to the low-resolution full disk magnetograms captured by Wilcox Solar Observatory in cycles 21-23. This approach revealed a set of more than 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 by variance (Zharkova et al, 2012), or 67% of the data by standard deviation.

The main pair of PCs is shown (Zharkova et al, 2015) to be associated with the two magnetic waves attributed to the poloidal magnetic field describing a double dynamo action in two different layers of the solar interior with dipolar magnetic sources in each layer. 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 (Shepherd et al, 2014, 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). 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 can naturally explain the difficulties in predicting sunspot activity with a single dynamo wave on a scale longer than one solar cycle (Karak & Nandy 2012). We showed that the sunspot activity (average sunspot numbers) is associated with the modulus summary curve (Zharkova et al, 2015), which is not a single wave as often assumed but a superposition, at least, of two waves, the PCs, used for production of the summary curve, from which one takes a modulus.

Recently, these solar activity prediction results about the modern GSM in cycles 25-27 were confirmed by the other researchers (Kitiashvili 2020; Obridko et al. 2021), who were using the same WSO synoptic magnetic field data and compared the spectra of the zonal harmonics of the SBMF and 3D solar dynamo models. Furthermore, Velasco Herrera et al. (2021) applied the machine learning (ML) algorithm to the averaged sunspot numbers taken from the International Sunspot Number (SSN) from the World Data Center Sunspot Index and Long-term Solar Observations reporting the modern Grand Solar Minimum to occur in cycles 25-27, exactly as reported by Zharkova et al. (2015).

In the current paper we show that the application of the appropriate statistical method used to reproducing the highly oscillating function of solar activity (Zharkova et al, 2015) by a set of periodic functions cosines allows us to extrapolate the solar magnetic field rather accurately backward three thousand years. We also highlight the essential differences of the solar activity curve reconstructed by us in the current paper from the recent long-term reconstruction of solar activity based on the terrestrial carbon 14 and beryllium 10 isotope dating and using a linear regression method for their extrapolation (Usoskin et al. 2002, 2004; Solanki & Krivova 2011). Moreover, we show below that Spoerer minimum derived by this reconstruction is likely to be an artefact of the terrestrial and Galactic activity caused by supernovae and not associated with solar activity.

Restoration of double dynamo waves for the past three millennia

As in our previous papers (Zharkova et al, 2015, 2020) we tested the original magnetic field data from full disk magnetograms for the past 3 solar cycles (21-23) with Principal Component Analysis and derived the eigen values and eigen vectors of solar oscillations. These came in pairs, with the highest eigen values of variance considered as the two principal components (PCs) associated with the dipole magnetic sources in both layers. These waves can be closely reproduced by the simulated waves derived from the two-layer dynamo model with meridional circulation (Zharkova et al, 2015) similar to the two cells reported from the helioseismic observations (Zhao et al, 2013)

There are rather stable magnitudes of the eigen values of these two dynamo waves for each and every solar cycle considered proving that the parameters of own oscillations of the Sun are maintained the same over a large period of time (millennia). This is re-assuring a very good health of the Sun’s dynamo machine. The variations of the dynamo wave parameters occur owing to different conditions in these two layers where the waves are generated leading to their 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 and grand minima occurring every 350-400 years shown in the past millennium (see Fig.3 in Zharkova et al, 2015).

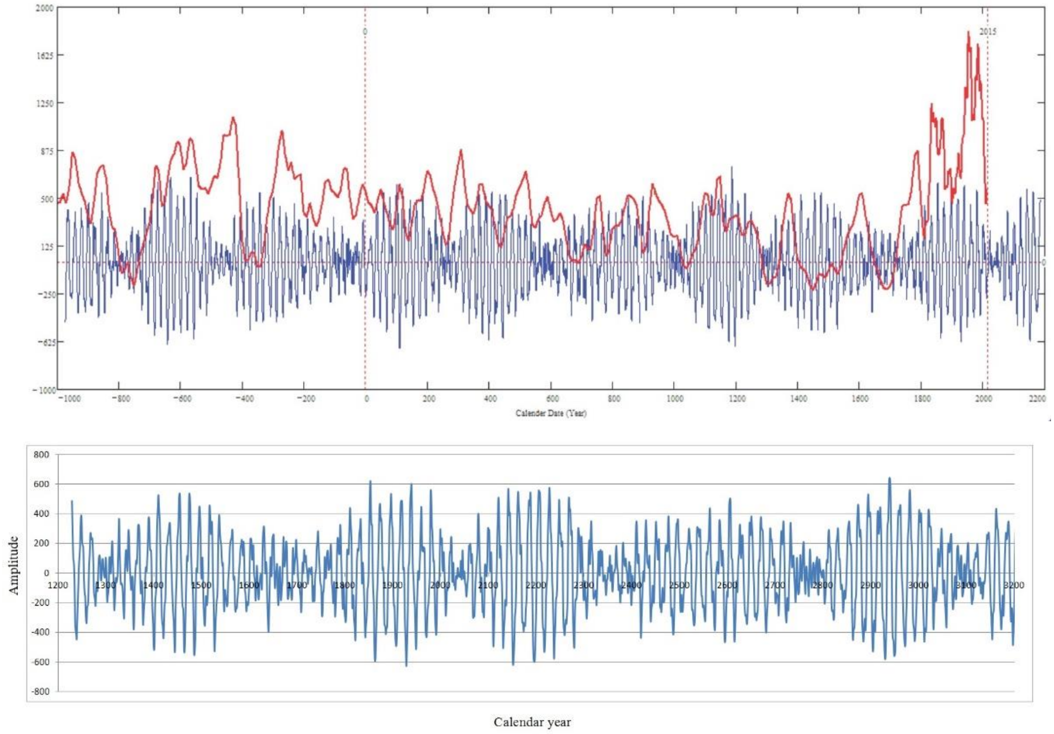

Figure 1. *Top plot: solar activity prediction backwards 3000 years with a summary curve (blue line) of the two principal components (PCs) of solar background magnetic field (SBMF) (Zharkova rt al, 2015) derived from the full disk synoptic maps of Wilcox Solar Observatory for cycles 21-23 versus the reconstruction by Solanki et al. (2004) (red line) by merging the sunspot curve (17-21 centuries) and carbon dating curve (before the 17 century). The bottom plot: the summary curve of two PCs calculated for 1200-3200 years (Zharkova et al., 2015)*

In the current paper we extend this extrapolation 3000 years backwards to 1000 BC as shown in Fig.1 (top plot, blue curve). For comparison, we have overplotted the curve of the solar activity reconstructed by Solanki et al 13, 15-17 from the average sunspot numbers observed before the 17 century and from the isotope Δ^{14}C and ^{10}Be abundances in earlier years (9-16 centuries) (top plot, red curve).

It can be noted that our summary curve extended by 3000 years backward (up to 1000 BC) in Fig. 1 is rather different from the curve reconstructed by Usoskin and Solanki et al (Solanki et al. 2004; Usoskin et al. 2004; Solanki & Krivova 2011). We believe, these differences are caused by the inaccuracies of reconstruction of a periodic function of solar activity by a linear regression analysis used by these authors, which is, in fact, only applicable to the normal data (with Gaussian distribution).

Whilst our reconstruction summary curve uses a Hamiltonian regression analysis with periodic cosine functions for reproduction of the oscillatory curve of solar activity (see Methods section). The curve reveals a remarkable resemblance to the sunspot and terrestrial activity reported in the past years 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 in the past millennia reveal the presence in solar activity of a grand cycle with a duration of about 350-400 years with the next grand cycle minimum (we call it a Modern minimum) approaching in 2020-2053 (Zharkova et al, 2015, Zharkova, 2020).

The long-term 'grand' cycle was previously considered as a 300-400 year cycle superimposed on the 22 year cycle using the observations of aurorae, periods of grape harvests etc. (Kingsmill 1906; Wagner et al. 2001). These periods are close to the period of a grand cycle (350-400 years) reported by Zharkova et al, 2015 as plotted in Fig.1 (bottom plot) and extended to further 3 millennia in Fig.1 (top plot).

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 in the two layers: a deeper layer close to the bottom of the Solar Convective Zone (SCZ) and shallow layer close to the solar surface for these different grand cycles and their individual solar cycles, whose physical conditions define the frequencies and amplitudes of dynamo waves generated in these layers. The larger the difference between these frequencies the smaller the number of regular 22 years cycles and the higher their amplitudes.

In addition to the grand cycle of 350-400 years, by combining the curves in Fig.1 (top plot, blue curve) and the curve used for the prediction for the next 1000 years in Fig. 3 of Zharkova et al (2015) reproduced in Fig. 1 (bottom plot), one can also note a larger *super-grand cycle* of about 2000-2100 years (Hallstatt's cycle), which is often reported in the spectral analysis of solar and planetary activity (Steinhilber et al, 2009, 2012; Zharkova et al., 2019). This super-grand cycle can be distinguished by comparing the five grand cycles in Fig. 1 (bottom plot) (years 1001-3000 AD) with the next 5 grand cycles restored for 1000 BC-1000 AD) (top plot), which clearly show the same repeating patterns for every 5 grand cycles (Zharkova et al, 2019).

There are the other 3 pairs of the significant independent magnetic field components (Zharkova et al, 2012), which are associated with quadruple magnetic sources in these layers, which can further modify the individual variations of 22 year cycles within each grand cycle (Zharkova et al, 2022). Although, quadruple waves (covered by smaller variance) have much smaller amplitudes, they are expected to modify solar activity to reproduce intermediate minima similar to Dalton's minimum (Popova et al, 2018).

However, there is another minimum, Spoerer's one (1450-1550), which is also not present in our summary curve (the blue curve) plotted in Fig.1, which shows during the same period of time a maximum of the grand cycle. In this case even the inclusion of quadruple components is unlikely to account for the major solar minimum, like Spoerer one, which has the properties of a grand minimum but in the absolutely wrong time. We discuss the discrepancy of Spoerer minimum in one of the sections below.

Verification of the solar activity from PCA with historic observations

Let us first check the evidences from the solar-terrestrial environment in the previous grand cycle in 14-16 century and the presence of the grand maximum when Spoerer minimum occurred plotted in Fig.2 as the summary curve.

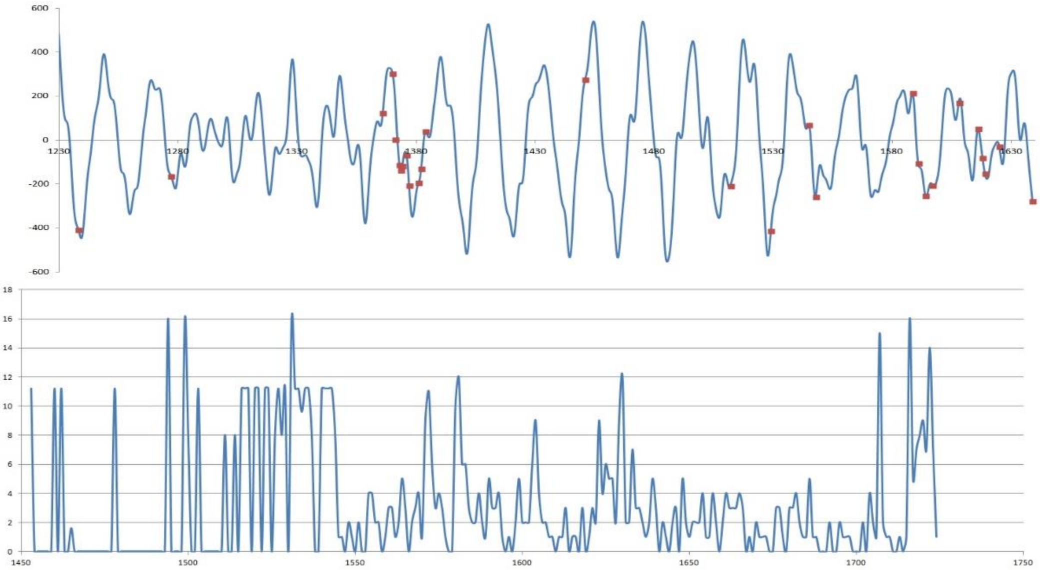

Figure 2. *Top plot: verification of the summary curve (blue line) with large sunspots (red dots) derived from the pre-telescope visual observations for the time of Sporer minimum. Bottom plot: distributions of terrestrial auroras over the period of Spoerer minimum revealing the strongest auroras ever observed. The auroras are widely observed all over the central Europe and often reached Mediterranian countries.*

The first verification comes from the pre-telescope observations of large sunspots observed (when possible) with the naked eye by Chinese and Japanese astronomers in the 13-16 centuries (Williams 1873; Wittmann 1978; Wittmann & Xu 1987) presented in Fig. 2, top plot. It can be seen that in the times when the large sunspots were observed they fit extremely well the individual solar cycles predicted by our summary curve in the 13-14 centuries prior to the alleged Spoerer minimum. It can be also seen that the pre-telescope observations of large sunspots in the 14-15 centuries done by Chinese astronomers (Wittmann 1978; Wittmann & Xu 1987) were rather patchy in the 14-15 centuries. They did not show any signs of a minimum of solar activity during the two cycles before and after 1380, which fit rather closely our predictions of the summary curve for these cycles.

Then during 1450-1550 (the alleged Spoerer minimum) there were also two large sunspots observed with a naked eye (see Fig.2, top plot), while during the next large solar minimum in the 17th century, Maunder Minimum, there were no large sunspots reported at all by any researchers even with telescopes, and the sunspot numbers were very small. This makes Spoerer minimum with two large sunspots a bit peculiar minimum, and we discuss its further in the sections below.

The second verification occurs from the reconstruction of the terrestrial temperature in Northern hemisphere compiled from 6 different sources as reported by Usoskin et al. (2005) (see Fig.2, bottom plot). It clearly shows that the temperature variations between 1450-1600 have a clear maximum and not the minimum as one could expect if the solar activity had the Sporer minimum. For example, for Maunder Minimum the terrestrial temperature goes through a well defined minimum seen clearly in the same Fig.2, bottom plot) from Usoskin et al. (2005).

The third verification comes from very strong auroras a reported in 14-16 centuries over ll over the skies of the whole Europe including Germany, Poland, Switzerland and even Portugal with other Mediterrenian countries (Schlamminger 1990; Schroder & Treder 1999). For this particular grand cycle in Fig.2 (bottom plot) we present the intensities of auroras during the period of Spoerer minimum. Similar to the terrestrial temperatures above, strong auroras coincide with the *maxima* of solar activity and not with its minima and, especially, not with the prolonged minimum as Spoerer's one is assumed to be. It is clear that the intensities of these unusual auroras in 14-16 centuries significantly exceed the intensities of the auroras ever observed on Earth in the past 500 years s (Schlamminger 1990; Schroder & Treder 1999) and, definitely, they do not have lower intensities expected for a deep solar minimum.

The butterfly diagrams for Maunder and Modern grand minima

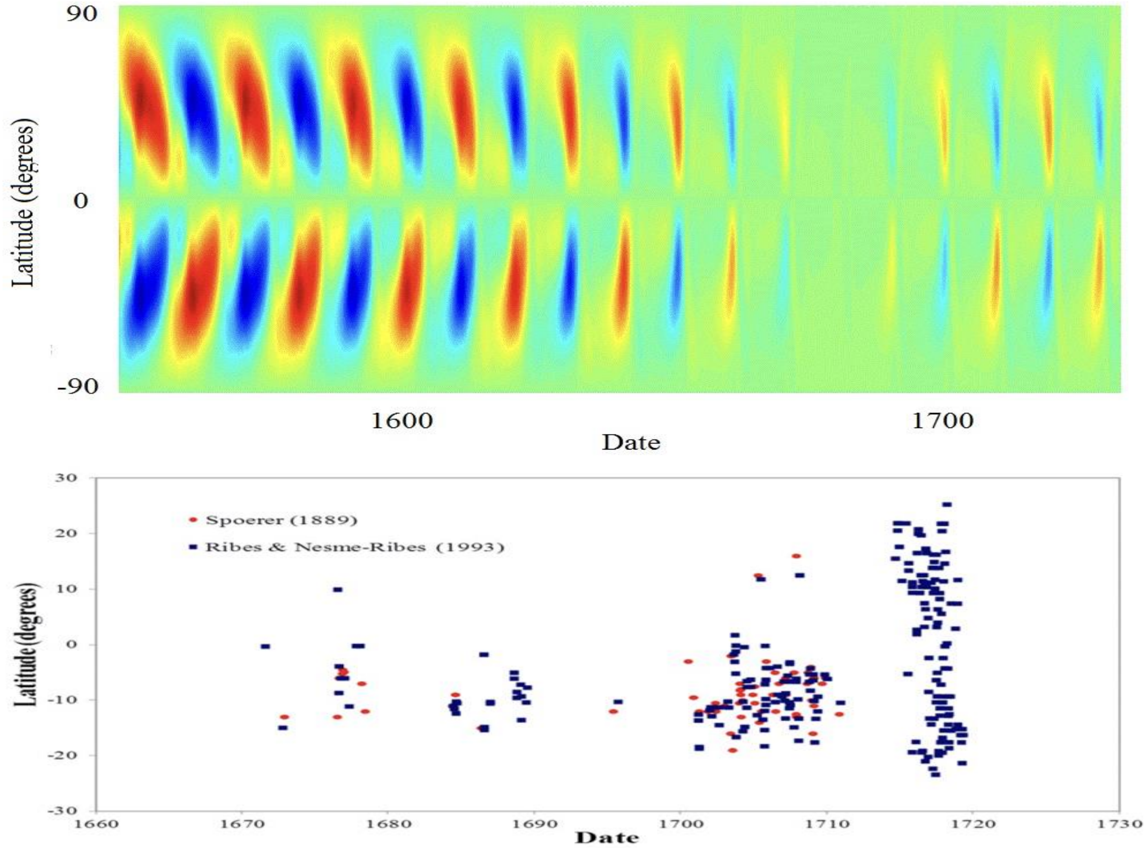

Figure 3. *Top plot: The butterfly diagram derived from the reported observations of sunspots for the Maunder minimum in the 17th century. Bottom plot: the simulated butterfly diagram using the same model for the parameters of magnetic field derived from PCA as shown in Fig. 1*.

The fourth independent verification of our reconstruction of solar activity in Fig. 1 comes from a comparison of the observed butterfly diagrams for the past Maunder minimum from 17th century (Eddy 1976, 1983) plotted in Fig.3 (top plot) with the theoretical butterfly diagram in Fig.3 (bottom plot). The theoretical butterfly diagram is derived from the two principal components of solar toroidal magnetic field, generated by the double solar dynamo with dipole sources in two different layers with meridional circulation (Zharkova et al, 2015). It can be seen that the simulated butterfly diagrams for the Maunder minimum occurred between the two grand cycles plotted in Fig.3 show a reasonable 'face fit' to the observed one in terms of their emergence timing and latitudes. For example, the observations show that the sunspots emerge in narrow strips of the times about 1690, 1705 and 1718 followed by the gaps between them without any sunspots (Eddy 1976, 1983). These gaps are also shown in the simulated diagram in the bottom plot with the largest gap clearly occurring between 1690 and 1705, similarly to the one shown in the observations (top plot).

In order to understand what kind of sunspot activity one can expect in the forthcoming grand minimum, we also simulate the butterfly diagrams for this modern grand solar minimum started in 2020 as plotted in Fig.4 (bottom plot) and for the period of 2000 years (1200-3200) with the five grand cycles from Zharkova et al, 2015) plotted in Fig.4 (top plot). It is evident from Fig.1 that the upcoming Modern minimum in the 21st century (2020-2055) is expected to last only for 3 standard 11 year cycles (25-27) and, thus, to be much shorter compared to the Maunder Minimum in the 17 century. There are also more sunspots expected to appear in the individual strips of the butterfly diagram, compared to the previous grand minimum, with the number of spotless gaps between the burst of sunspot activity to be the same as in the Maunder minimum (see Fig.4 (bottom plot)). The next extended grand minimum resembling Maunder minimum is expected after the next grand cycle in 2060-2420 (see Fig.1, bottom plot). This trend

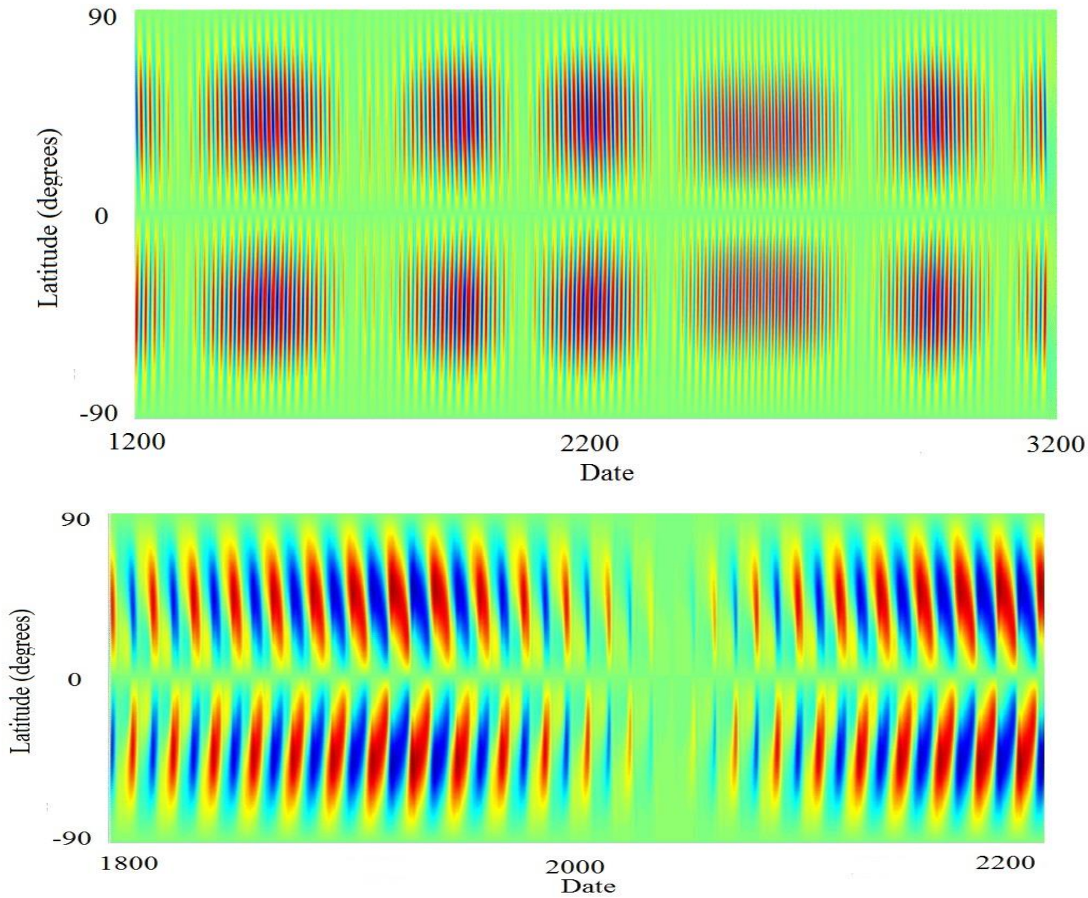

Figure 4. *The butterfly diagrams calculated for the dynamo model in the solar interior with two cells as derived from HMI/SDO observations by Zhao et al, 2013 having the opposite meridional circulation (Zharkova et al, 2015) for the period of 1200 to 3200 years (top plot) and for the upcoming Modern grand minimum in 2020-2055 (bottom plot).*

is confirmed by the numbers of spotless days observed for the current cycle 25 which is in the ascending phase until 2024 (see https://wwwbis.sidc.be/silso/spotless).

Solar activity during Spoerer minimum and possible effects of supernovae

One can note that Spoerer's minimum (1450–1550) indicated by Eddy (1976, 1983) is not present in our summary curve plotted in Fig. 1, as pointed out by Usoskin and Koval'stov (2015) showing a maximum of the solar grand cycle during the same period of time. Moreover, after investigating the method of the time dating with $\Delta^{14}C$ isotope (Libby 1946; Arnold & Libby 1949) and considering the terrestrial and extra-terrestrial conditions reported in the literature (Williams 1873; Wittmann 1978; Schroder & Treder 1999), we are puzzled with a question about the validity of assigning the abundances of $\Delta^{14}C$ and ^{10}Be to the minimum of solar activity in the period of the alleged Spoerer minimum. If one assumes that, indeed, it was a long Spoerer minimum in solar activity in the 14-16 centuries, as suggested by the Holocene curve derived from restoration of the carbon 14 isotope abundances (Eddy 1976; Usoskin et al. 2004; Solanki & Krivova 2011), 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 (Fig.2, top plot), strongest auroras ever observed on the Earth (Fig.2, bottom plot) and cosmic ray intensity in that period (McCracken & Beer 2007).

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 cycle for these centuries was not much different from the previous and the next grand cycles (which we are experiencing now) as shown in Fig. 1. Furthermore, there was an area increases recorded in Antarctic while the Arctic ice reveals the signs of area decreases as it should be during a normal solar activity that can be explained by the very southern location of the supernova Vela Junior not affecting the northern hemisphere. In addition, the terrestrial temperature in the period of Spoerer minimum had, in fact, a maximum and not minimum as expected during large solar minima (Zharkova et al, 2018).

We reckon that Spoerer minimum is, in fact, an artefact of the reconstruction techniques used (Usoskin (Solanki et al. 2004; Usoskin et al. 2004), where a linear regression analysis developed for data with normal distribution (Good & Hardin, 2009) was applied to the strongly oscillating function describing the variations of sunspot numbers in the past 400 years contrary to our method using special periodic functions to account for these oscillations. One of the examples of fitting incorrectly the oscillating function with a linear regression approach is shown by Akasofu (2010) (see their Fig. 9), when explaining the modern era recovery of the Earth from the little ice period and the incorrect use of a linear part of the temperature variations for the extremely incorrect prediction of the terrestrial temperature growth in the next century.

Possible uncertainties in the carbon dating approach

By default, the accuracy of the carbon dating method is dependent on the knowledge of the background radiation at the evaluation periods as indicated by Libby (Arnold & Libby 1949). Normally, the calculations of carbon dating produce dates in radiocarbon years: i.e. dates that represent the age the sample would be if the $^{14}C/^{12}C$ ratio had been constant historically (Taylor & Bar-Yusef 2014).

Libby's original exchange reservoir hypothesis assumed that the $^{14}C/^{12}C$ ratio in the exchange reservoir is constant all over the world and gives an error about 80 years.

Then later Libby had pointed out as early as 1955 the possibility that this assumption was incorrect, it was not until discrepancies began to accumulate between the measured ages and the known historical dates for artefacts that it became clear that a correction would need to be applied to radiocarbon ages to obtain calendar dates (Aitken 1990; Taylor & Bar-Yusef 2014).

Any addition of carbon to a sample of a different age will cause the measured date to be inaccurate. Contamination with modern carbon causes a sample to appear to be younger than it really is: the effect is greater for older samples while contamination with old carbon, with no remaining ^{14}C, causes an error in the other direction independent of age – a sample contaminated with 1% old carbon will appear to be about 80 years older than it really is, regardless of the date of the sample (Aitken 1990).

There are several causes of variation in the ratio across the reservoir, which can significantly increase the errors (see, e.g., Damon and Sonett, 1991): variations of the cosmic-ray flux on a geological timescale due to the changing galactic background (e.g., a nearby supernova explosion or crossing the dense galactic arm); secular-to-millennial variations are caused by the slowly-changing geomagnetic field or by solar magnetic activity; mixing of atmospheric carbon with the surface waters, 'marina effects' or water running from aged rocks and volcanic eruption and even differences in atmospheric circulation in hemispheres. While the variations of the terrestrial magnetic field and solar activity were actively considered in the past (Usoskin et al, 2004, Solanki and Krivova, 2011) 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 Spoerer minimum is discussed in the section below.

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

The strong increase of the cosmic rays in 14-15 centuries was already reported by McCracken and Beer (2007). Here we suggest that this increase was caused by supernovas, which 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 (Baade & Zwicky 1934; Ruderman 1974; Atri & Melott 2014; Thomas et al. 2016) 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 (Bowman 1995) including Libby (1946) who introduced this method.

Also a near-Earth supernova can produce noticeable effects on terrestrial biosphere by destroying to large extent its ozone layer (Gehrels et al. 2003; Becker Tjus et al. 2016) if it occurred as far as 700-3000 light-years away depending upon the type and energy of the supernova. Gamma rays from a supernova would induce a chemical reaction in the upper atmosphere converting molecular nitrogen into nitrogen oxides, depleting the ozone layer enough to expose the surface to harmful solar radiation. This has been proposed as the cause of the Ordovician–Silurian extinction, which resulted in the death of nearly 60% of the oceanic life on Earth (Melott et al. 2004). It was noted that the traces of past supernovae might be detectable on Earth in the form of metal isotope signatures in rock strata as iron-60 enrichment was later reported in deep-sea rock of the Pacific Ocean (Knie et al. 2004). Then later the elevated levels of nitrate ions were found in Antarctic ice (Motizuki et al. 2010, which coincided with the 1006 and 1054 supernovae of our Galaxy. Gamma rays from these supernovae could have boosted levels of nitrogen oxides, which became trapped in the ice (Motizuki et al. 2010).

In Fig. 5 we overplotted on the summary curve all the supernovae occurred in the past 2000 years (top plot) and made a close-up plot of the supernovae occurred prior and after the alleged Sporer minimum shown in bottom plot. The remnant of a mysterious supernova Vela Junior, which became a neutron star, was found in 1998 (Iyudin et al. 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.

This supernova was located at 46 degrees south that may have been too far south for the 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-telescope era.

This location of supernova Vela Junior can explain the paradoxal contradiction occurred in the SN reconstructions based upon the Greenland data (Usoskin et al. 2004). Contrary to the Antarctic ice data (the solid curve named An), the ^{10}Be data from Greenland exhibits the very pronounced maxima in 1500 and in 1560 when it was supposed to be Spoerer minimum. Also it is clearly seen that during the Maunder Minimum, or after 1650, the both An and Gr curves become rather consistent showing the minimum of solar activity (Usoskin et al. 2004).

We suggest that the cosmic rays from another supernova, Tycho's supernova (Brahe & Kepler 1602), combined with the effect of Kepler's supernova (Kepler 1609; Kepler et al. 1627) occurred just 32 years later changed the terrestrial background to very high magnitudes of carbon 14 isotope that led to the occurrence of Spoerer minimum, which is, in fact, not related to solar activity at all. This suggestion is proved by the fact Tycho Brahe's supernova remnant is still the most intense γ-ray source in the night sky (Lu et al. 2011) meaning that 500 years ago the stream of cosmic rays from this supernova was enormous as reported before and caused the most powerful terrestrial auroras ever observed.

Hence, the links of supernovae with the solar activity curve derived for the 14-16 century from the carbon dating (Usoskin et al. 2002; Solanki et al. 2004)can be summarised as follows.

1. High abundances of $\Delta^{14}C$ time-dated to 14-16 centuries leading to assumption of the Spoerer solar minimum can be created prior this time because of the occurrence in the 13 century of supernova observed in the Southern hemisphere with the Imaging Compton Telescope (COMPTEL) at the distance of only 700 light years (Iyudin et al. 1998).

2. The most intense supernova observed by Tycho Brahe (Brahe & Kepler 1602) in 1572 in our galaxy at the distance of 3200 light years that was after the Spoerer minimum and whose radiation could contaminate the samples with carbon 14 used for dating of earlier events.

3. There was also other supernova observed in 1604 by Kepler (the last supernova in our galaxy) (Kepler 1609)(see Fig.5 and a few other supernovas from our galaxy in the 12-18 centuries).

Many of these supernovae originated from the Milky Way's galaxy core proving that the galactic core was very active in the pre- and early telescopic era, providing the most extensive streams of cosmic rays during the supernova formation preceding or coinciding with Spoerer minimum derived in $\Delta^{14}C$ on the Earth. Tycho Brahe's and Kepler's supernovae could change significantly the background radiation of the Earth, contaminate the samples used for the carbon dating and lead, in turn, to errors in carbon 14 dating, if this background is not taken into account.

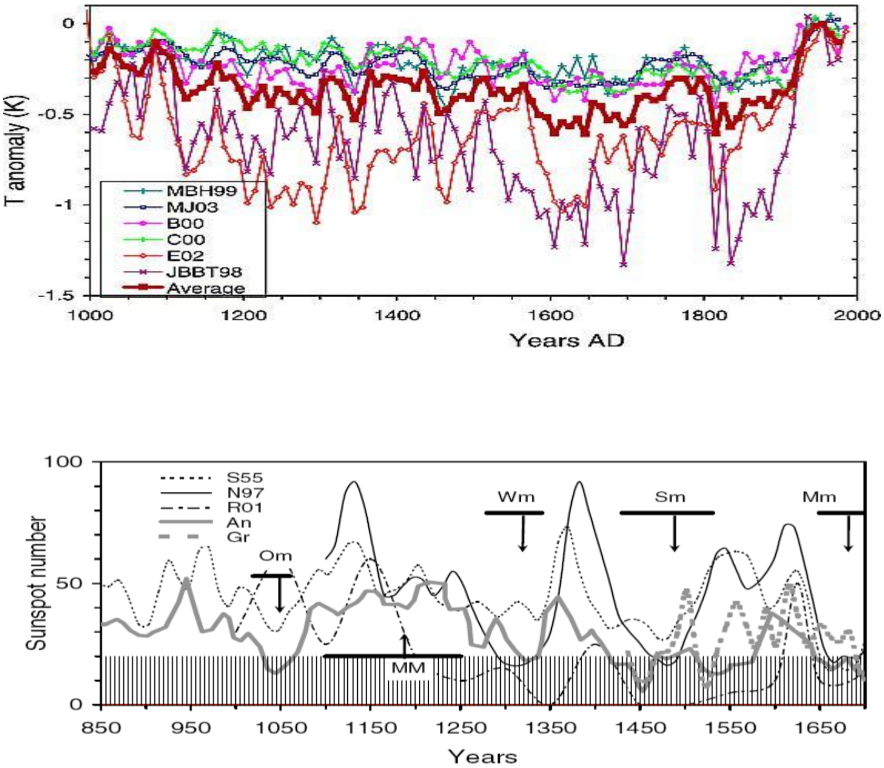

Figure 5. *Top plot: the terrestrial temperature variations derived by Usoskin et al. (2005)· Bottom plot: The sunspot plots versus ice variation in Greenland (Gr) and Antarctic (An) from Usoskin et al. 2004.*

Conclusions

In this paper we reproduce the summary curve for the last 3000 years and showing 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) and so on. We verify the extrapolated summary curve of the principal components of the solar background magnetic field, as a new 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 butterfly diagrams for the Maunder Minimum.

We confirm the prediction of the modern grand minimum in 2020-2053 (Zharkova et al, 2015, Zharkova 2020), which already started in cycle 25 to have the sunspot activity reduced with a further decrease of solar magnetic field and sunspot numbers in cycles 26 and 27.

We argue that Spoerer 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 in ~1280 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 diseases 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.

In addition, the supernovae observed by Tycho Brahe and Kepler brought very powerful cosmic rays, which, in turn, affected the Earth atmosphere and surface creating a very strong nuclei background much different from the standard one accepted in the carbon dating. This increased background intensity can definitely introduce the time-dating error of a few hundred years providing a plausible explanation why Spoerer minimum did not exist in the solar magnetic field summary curve in the 15-16 centuries derived with the principal component analysis and symbolic regression classification of solar magnetic field, which reveals in Fig. 1 only a normal maximum of the grand cycle.

Given the number of grand solar minima and grand solar maxima correctly fit, combined with the other means of verification discussed above, we can confidently reinforce our previous findings (Zharkova et al, 2015) that the solar activity is produced by two magnetic waves, or PCs, as derived from the full disk magnetograms in cycles 21-24, which are proven to be generated by a double solar dynamo in inner and outer layers of the solar interior. This finding also emphasizes the fact that the solar activity has a very well-maintained periodicity of its dynamo waves maintained over three millennia that reflects a good health of the solar dynamo of the Sun.

References

Ackermann, M., Ajello, M., Allafort, A., et al. 2013, Science, 339, 807
Aitken, M. J. 1990, Science-based Dating in Archaeology (London: Longman), 404
Arnold, J. R. & Libby, W. F. 1949, Science, 110, 678
Baade, W. & Zwicky, F. 1934, Proceedings of the National Academy of Science, 20, 259
Becker Tjus, J., Eichmann, B., Kroll, M., & Nierstenhöfer, N. 2016, Astroparticle Physics, 81, 1
Bowman, S. 1995, 64
Brahe, T. & Kepler, J. 1602, Tychonis Brahe Astronomiae instauratae progymnasmata : quorum haec prima pars de restitutione motuum SOLIS et lunae stellarumque inerrantium tractat, et praeterea de admiranda nova stella anno 1572 exorta luculenter agit. (Typis inchoata Vraniburgi Daniae, absoluta Pragae Bohemiae : [s.n.])
Brandenburg, A. & Subramanian, K. 2005, Phys. Rep., 417, 1
Damon, P. E. & Sonett, C. P. 1991, in The Sun in Time, ed. C. P. Sonett, M. S. Giampapa, & M. S. Matthews, 360–388
Eddy, J. A. 1976, Science, 192, 1189
Eddy, J. A. 1983, Sol. Phys., 89, 195
Iyudin, A. F., Schönfelder, V., Bennett, K., et al. 1998, Nature, 396, 142
Jones, C. A., Thompson, M. J., & Tobias, S. M. 2010, Space Sci. Rev. , 152, 591
Karak, B. B. & Nandy, D. 2012, Astrophys. J. Lett., 761, L13
Kepler, J. 1609, Astronomia nova. (Pragae)
Kepler, J., Brahe, T., & Eckebrecht, P. 1627, Tabvlae Rudolphinae, qvibvs astronomicae scientiae, temporum longinquitate collapsae restauratio continetur
Kingsmill, T. W. 1906, Nature, 73, 413
Knie, K., Korschinek, G., Faestermann, T., et al. 2004, Physical Review Letters, 93, 171103
Libby, W. F. 1946, Physical Review, 69, 671
Libby, W. F. 1963, J. of Geophys. Res., 68, 2933
Lu, F. J., Wang, Q. D., Ge, M. Y., et al. 2011, Astrophys. J. , 732, 11
McCracken, K. G. & Beer, J. 2007, Journal of Geophysical Research (Space Physics), 112, A10101
Melott, A. L., Lieberman, B. S., Laird, C. M., et al. 2004, International Journal of Astrobiology, 3, 55
Motizuki, Y., Naka, Y., & Takahashi, K. 2010, Highlights of Astronomy, 15, 630
Motizuki, Y., Takahashi, K., Makishima, K., et al. 2009, ArXiv e-prints
Obridko, V. & Nagovitsyn, Y. 2014, in COSPAR Meeting, Vol. 40, 40th COSPAR Scientific Assembly
Parker, E. N. 1955, Astrophys. J. , 122, 293
Pesnell, W. D. 2008, Sol. Phys., 252, 209
Popova, E., Zharkova, V., & Zharkov, S. 2013, Annales Geophysicae, 31, 2023
Popova, E., Zharkova, V., Zharkov, S. & Shepherd S.J., 2018, JASTP, 176, 61
Reischauer, O., Fairbank, J. K., & Craig, A. M. 1960, 64
Scafetta, N. 2014, Astrophysics and Space Science, 354, 275
Schlamminger, L. 1990, Mon. Notices of RAS, 247, 67
Schove, D. J. 1948, Popular Astronomy, 56, 247
Schroder, W. & Treder, H. J. 1999, Geofisica Internecional, 39, 197
Sekido, Y., Masuda, T., Yoshida, S., & Wada, M. 1951, Physical Review, 83, 658
Shepherd, S. J., Zharkov, S. I., & Zharkova, V. V. 2014, Astrophys. J. , 795, 46
Solanki, S. K. & Krivova, N. A. 2011, Science, 334, 916

Solanki, S. K., Usoskin, I. G., Kromer, B., Schu ̈ssler, M., & Beer, J. 2004, Nature, 431, 1084
Taylor, R. E. & Bar-Yusef, O. 2014, Radiocarbon Dating: Archaeological Perspective (Routledge), 404
Usoskin, I. & Kovaltsov, G. 2015, ArXiv e-prints
Usoskin, I. G. 2013, Living Reviews in Solar Physics, 10
Wagner, G., Beer, J., Masarik, J., et al. 2001, Geophys. Res. Lett., 28, 303 Williams, J. 1873, Mon. Notices of RAS, 33, 370
Wittmann, A. 1978, Astron. and Astrophys., 66, 93
Zhao, J., Bogart, R. S., Kosovichev, A. G., Duvall, Jr., T. L., & Hartlep, T. 2013, Astrophys. J. Lett., 774, L29
Zharkova, V. V., Shepherd, S. J., & Zharkov, S. I. 2012, Mon. Notices of RAS, 424, 2943
Zharkova, V. V., Shepherd, S. J., Popova, E., & Zharkov, S. I. 2015, Nature Scientific Reports, 5, 15689
Zharkova, V. V., Shepherd, S. J., Popova, E., & Zharkov, S. I., 2018, JASTP, 176, 72
Zharkova, V. V., Shepherd, S. J., Popova, E., & Zharkov, S. I. 2019, Nature Scientific Reports, 9, 9197
Zharkova, V.V., 2020, Temperature, 7:3, 217-222, DOI: 10.1080/23328940.2020.1796243,
Zharkova, V.V., 2021, chapter in the book Solar System Planets and Exoplanets, DOI: