Solar Physics (2004) 224: 37–47

Review Paper

LONG-TERM SOLAR ACTIVITY: DIRECT AND INDIRECT STUDY

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(Received 1 September 2004; accepted 23 September 2004)

Abstract. The series of directly observed sunspot numbers is nearly 400 years long. We stress that the recently compiled group sunspot number series is an upgrade of the old Wolf series and should always be used before 1850. The behavior of solar activity on longer time scales can be studied only using indirect proxies. Such proxies as aurorae occurrence or naked-eye sunspot observations are qualitative indicators of solar activity but can be hardly quantitatively interpreted. Cosmogenic isotope records provide a basis for quantitative estimate of the past solar activity. Here we overview the main methods of the long-term solar activity reconstruction on the centennial to multimillennia time scale. We discuss that regression-based reconstructions of solar activity lead to very uncertain results, while recently developed physics-based models raise solar activity reconstruction to a new level and allow studying its behavior on a multimillennia time scale. In particular, the reconstructions show that the recent episode of high solar activity is quite unusual in the multimillennia time scale.

1. Introduction

The sunspot number (SN) series is the longest record of directly observed solar activity, which started in 1610 and covers about 400 years. During this period SN was varying between the nearly spotless Maunder Minimum and the recent unusually high activity when SN reached the average value of about 75. The main features of solar activity on the decennial–centennial time scale were summarized, e.g., by Vitinsky (1986) or Usoskin and Mursula (2003). However, it is important to know the behavior of solar activity on even longer time scales for many reasons, in particular for the solar/stellar dynamo theory and for research on long-term solar-terrestrial relations (“space climate”). Since there were no regular observations in the pre-telescopic era, indirect methods are used for the purpose. Here we overview the main methods and results of the long-term solar activity reconstruction on the centennial to multimillenial time scale.

2. Sunspot Number Series

Until recently the longest series of sunspot observations was the famous Wolf sunspot number (called WSN henceforth) which was primarily compiled by Rudolf

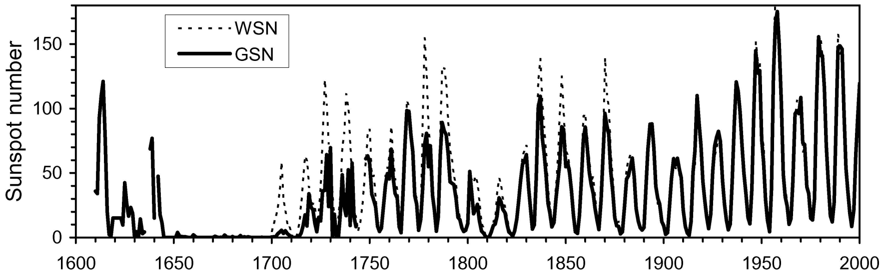

Figure 1. The annual series of sunspot numbers: Group sunspot numbers (GSN, *solid line*) and Wolf sunspot numbers (WSN, *dotted line*).

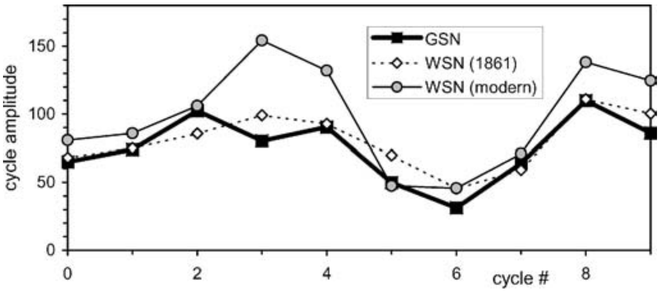

Figure 2. The amplitude of solar cycles according to GSN (*thick lines* and *black squares*), original WSN published in 1861 (*dotted line* with *open diamonds*) and the corrected "modern" WSN (*thin line* with *grey dots*).

Wolf of Zürich Observatory and then continued using the same method (Waldmeier, 1961) (since the 1980s WSN is provided by the Royal Observatory of Belgium). The official WSN starts in 1749, and before that only yearly WSN values are available (Figure 1). The WSN series uses only one (primary) observer for each day with all gaps being interpolated without notes (for details see, e.g., Hoyt and Schatten, 1998). Therefore, the WSN series is a combination of direct observations and interpolations for the period before 1849 with all the raw information hidden, which makes it impossible to estimate its uncertainties (see, e.g., Vitinsky *et al.*, 1986; Hoyt *et al.*, 1994; Wilson, 1998; Letfus, 1999). WSN contains not only sunspot but also geomagnetic data as illustrated by Figure 2. After publishing his original sunspot series in 1861 (Wolf, 1861), Wolf corrected it using the "magnetic needle" (geomagnetic inclination range) data measured in Milano (see the full story in Hoyt and Schatten, 1998). Note that the original WSN series is much closer to the Group spot numbers (GSN) than the corrected WSN which is widely used now. Thus, the WSN series can be analyzed only for the period since 1849 or, with caveats, since 1749.

Recently a new updated sunspot series, called the Group sunspot number (GSN) series (see Figure 1), was presented by Hoyt and Schatten (1998), which contains 80% more raw information and is more homogeneous than WSN (Hoyt and

Schatten, 1998; Letfus, 1999; Hathaway *et al.*, 2002). Although GSN still contain some uncertainties, it is important that all raw information is available which allows for independent re-analysis, error estimate, and statistical studies (Usoskin and Mursula, 2003). The GSN series is strongly recommended for analysis of sunspot activity before 1850. It should be noted that WSN and GSN are *not* different alternative proxies of solar activity but rather GSN is an upgrade of the WSN series. We note that even GSN series is not finalized, and new archival results on sunspot observations appear, filling some gaps in GSN (Vaquero, 2004).

3. Indirect Proxy

The only way to study solar activity in the pre-telescopic era is related to the so called indirect solar proxies.

Such a proxy is the record of visual observations of *aurorae borealis* in middle-latitudes which are caused by enhanced geomagnetic activity due to transient interplanetary phenomena (e.g., Schove, 1983; Silverman, 1983, 1992, 1998; Křivský and Pejml, 1988). Fragmentary records of aurorae can be found in Occidental and Oriental sources since antiquity. These data are sensitive to long-term changes of the geomagnetic field. Also, because of the phenomenon's short duration and low brightness, the probability of seeing aurora can be affected by a number of factors (clouds, the phase of the Moon, season, etc.). The fact that these observations were not systematic in early times makes it difficult to produce a homogeneous data set.

Some fragmentary data on *naked-eye observations* of sunspots exist for quite early times, mostly from Oriental sources (see, e.g., Clark and Stephenson, 1978; Wittmann and Xu, 1987; Yua and Stephenson, 1988). Spots on the Sun are mentioned in official Chinese and Korean chronicles from 165 BC to 1918 AD. While these chronicles are fairly reliable, these data are not straightforward to interpret since they can be influenced by meteorological or other phenomena (e.g., dust loading in the atmosphere due to dust storms or volcano eruptions facilitates sunspot observations). Moreover, records of sunspot observations in the official chronicles depended on the dominant traditions during specific historical periods. Direct comparison of the Oriental naked-eye sunspot observations and European telescopic data shows that the naked-eye observations can serve only as a qualitative indicator of the sunspot activity but can be hardly quantitatively interpreted (see, e.g., Willis, 1996 and references therein).

The most useful proxy of solar activity is formed by the data on *cosmogenic radionuclides*, e.g., ^{10}Be and ^{14}C, which are produced by cosmic rays in the Earth's atmosphere (e.g, Stuiver and Quay, 1980; Beer *et al.*, 1990; Bard, 1997; Beer, 2000). Cosmic rays are the major source of cosmogenic nuclides in the atmosphere (excluding anthropogenic factors during last decades) with the maximum production being in the upper troposphere/stratosphere. After a complicated transport in terrestrial reservoirs (atmosphere, ocean, biosphere) they are stored in natural archives such as polar ice, trees, marine sediments, etc. Because of the heliospheric modulation of the cosmic ray intensity at the Earth's orbit, the cosmogenic isotope production depends inversely on solar activity. An important advantage of the cosmogenic data is that primary archiving is done routinely in a similar manner throughout the ages, and these archives are measured nowadays in laboratories using modern techniques. If necessary, all measurements can be repeated and improved as has been done for some radiocarbon samples. In contrast to fixed historical archival data (such as sunspot or auroral observations) this approach, together with absolute independent dating of samples, allows for homogeneous data sets with stable quality. Cosmogenic isotope data are the only regular indicator of solar activity on the very long-term scale but they cannot always resolve details of individual solar cycles. Redistribution of the nuclides in the terrestrial reservoirs and archiving may be affected by local and global climate/circulation processes which are to a large extent unknown in the past. However, a combined study of different nuclides data, whose responses to terrestrial effects are very different, may allow for disentangling external and terrestrial signals.

4. Solar Activity Reconstruction from Proxy Data

4.1. MATHEMATICAL METHODS

There are numerous attempts to extend the sunspot series back in time using *extrapolations* of its statistical properties (e.g., De Meyer, 1998; Rigozo *et al.*, 2001). Actually, it is not a reconstruction based upon measured or observed quantities but rather a "post-diction." Although often used for predictions, such a method can hardly be applied for a reliable reconstruction of solar activity. In particular, it assumes that the time series is stationary, i.e. that all information on its future/past is contained in a limited time sample. Clearly such models cannot include periods exceeding the time span of observations upon which the extrapolation is based.

Regressions are the most used method of solar activity reconstruction from proxy data (see, e.g., Stuiver and Quay, 1980; Ogurtsov, 2004). A phenomenological regression (either linear or nonlinear) is built between proxy data set and the directly measured solar activity for the available "training" period (since 1750 for WSN or since 1610 for GSN). Then this regression is extended backwards to evaluate SN from the proxy data. The main shortcoming of the regression is that this method depends on the time resolution and "training" period. The former is illustrated by Figure 3 which shows the scatter plot of the ^{10}Be concentration vs. GSN for the annual and 11-year smoothed data. One can see that the slope of the ^{10}Be-vs.-GSN relation within individual cycles is significantly different (about -500 g/at) from the slope of long-term relation (about -100 g/at), i.e., individual cycles do not lie along the line of 11-year averaged cycles. Therefore, the formal regression built using the annual data for 1610–1985 yields a much stronger GSN-vs.-^{10}Be dependence

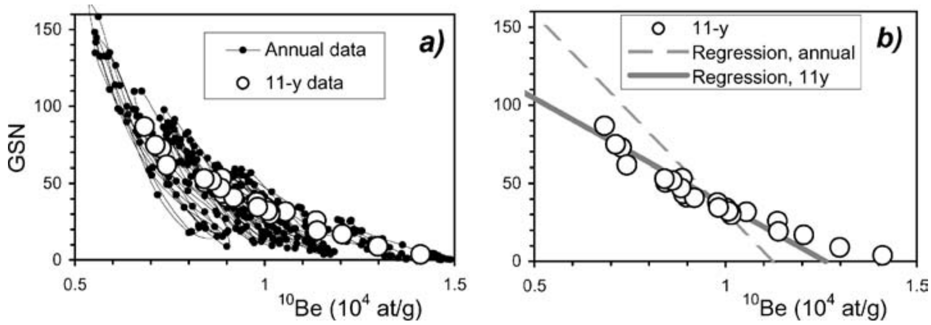

Figure 3. Scatter plot of smoothed group sunspot numbers vs. (2-year delayed) ^{10}Be concentration. (a) Annual (*connected small dots*) and 11-year averaged (*big open dots*) values. (b) Best-fit linear regressions between the annual (*dashed line*) and 11-year averaged values (*solid line*). The *dots* are the same as in panel (a).

than for the cycle-averaged data (see Figure 3b). Accordingly, when applying an annual-based regression to the long-term smoothed ^{10}Be (and other proxy) data may result in erroneous evaluation of the sunspot number. Also, the use of WSN instead of GSN before 1850 to build a regression can lead to additional errors in the reconstruction, since WSN overestimates the SN level for the eighteenth century (Section 2). We note that earlier regression works (before 1998 when Hoyt and Schatten published their final GSN series) were based on WSN series and should be revised.

Sometimes *a fit of a mathematical model to indirect proxy data* is used, which is a combination of the extrapolation and proxy methods. In such models a mathematical extrapolation is fitted to some proxy data for the time when direct data are not available, e.g., Schove (1955) fitted the slightly variable but phase-locked carrier frequency (about 11 years), to fragmentary data from naked-eye sunspot observations or auroral sightings. This approach has been recently modified using nonlinear relations (Nagovitsyn, 1997), but its shortcomings still limit the reliability of the reconstruction. We note that these works yield too high sunspot activity during the Maunder minimum.

4.2. PHYSICS-BASED MODELS

A new step in long-term solar activity reconstruction has been made recently, which is a development of the proxy method where physics-based models are used, instead of a phenomenological regression, to link SN with the cosmogenic isotope production (Beer *et al.*, 2003; Usoskin, 2003; Solanki, 2004). Due to recent theoretical developments, it is now possible to construct the chain of physical models to simulate the entire link between solar activity and cosmogenic data. The first model (Solanki, 2000, 2002) relates the open solar magnetic flux to SN (through the magnetic flux in sunspots). Although this model is based on physical principles, it contains one adjustable parameter, the decay time of the open flux, which cannot be measured or theoretically calculated and has to be found fitting the model to data. Open flux data since 1975 were used to fix this parameter (Solanki *et al.*, 2000, 2002). The open magnetic flux is directly related to the global interplanetary magnetic field which modulates the spectrum of cosmic rays at the Earth's orbit. The next model (Usoskin *et al.*, 2002a) calculates the cosmic ray spectrum $X(P, \Phi)$, where Φ is the heliospheric modulation strength and P is particle's rigidity, from the open magnetic flux. For studies of long-term changes of the cosmic ray flux, the parameter Φ alone adequately describes the modulation of the cosmic ray (Caballero-Lopez and Moraal, 2004). The connection between the cosmogenic isotope production rate, Q, at a given location and the cosmic ray flux is given by

$$Q(\theta) = \int_{P_c(\theta)}^{\infty} X(P, \Phi) \cdot Y(P)\, dP, \tag{1}$$

where θ is the geomagnetic latitude, P_c is the local cosmic ray rigidity cutoff, and $Y(P)$ is the differential yield function of cosmogenic isotope production (see Castagnoli and Lal (1980) for ^{14}C, and Masarik and Beer (1999) or Webber and Higbie (2003) for ^{10}Be). The abundance of ^{10}Be in polar ice is assumed to be directly proportional to its atmospheric production rate (Beer *et al.*, 1990, 2003; Masarik and Beer, 1999; Usoskin *et al.*, 2002a) owing to its short residence time in the atmosphere and relatively simple precipitation process. On the other hand, a complicated global carbon cycle is involved between the production of ^{14}C in the atmosphere and its final deposition in tree rings (see, e.g., Damon *et al.*, 1978; Stuiver and Quay, 1980). Because of the global nature of the carbon cycle and its long attenuation time, the radiocarbon is globally mixed before the final deposition, and Equation (1) should be integrated over the globe. Thus, a physics-based model exists for every step linking the solar activity to cosmogenic isotope content. The validity of this link was verified by Usoskin *et al.* (2002b) who calculated the expected concentration of ^{10}Be in polar ice from the GSN record and showed that it corresponds well to the measured concentration.

Inverting the physics-based model one can quantitatively evaluate the solar activity from the measured cosmogenic isotope abundance. Due to strong nonlinearity of the model, its inversion cannot resolve individual 11-year cycles, and only cycle-averaged slow changes of the solar activity can be reconstructed (Usoskin *et al.*, 2003, 2004). Using the data on ^{10}Be measured in Greenland and Antarctic ice, Usoskin (2003) reconstructed 11-year averaged SN since 850 AD (Figure 4). This result reproduces the four known grand minima of solar activity – Maunder (1645–1715), Spörer (around 1500 AD), Wolf (around 1300 AD), and tiny Oort (around 1050 AD) minima (cf., e.g., Peristykh and Damon, 2003). Later Solanki *et al.* (2004) reconstructed 10-year averaged sunspot numbers from the ^{14}C content in tree-rings throughout the Holocene and estimated its uncertainties (see Figure 4). The slightly negative values during the grand minima are an artifact, they are compatible with

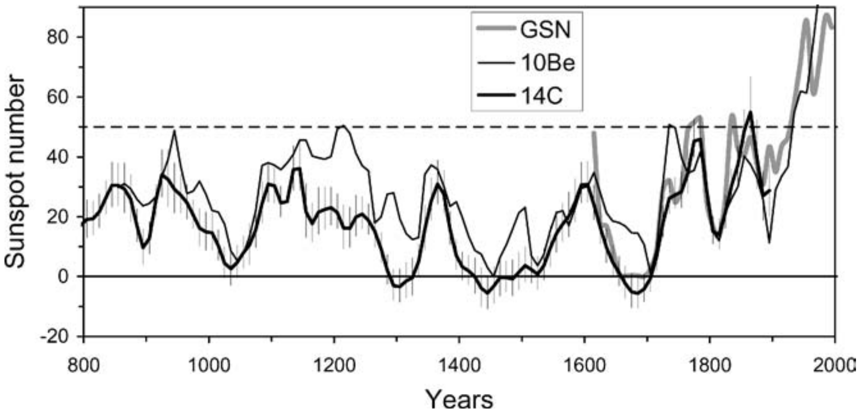

Figure 4. 10-year averaged sunspot numbers: Actual group sunspot numbers (*thick grey line*) and the reconstructions based on ^{10}Be (thin curve, Usoskin, 2003b) and on ^{14}C (*thick curve* with error bars, Solanki, 2004). The *horizontal dotted line* depicts the high activity threshold, 50.

the absence of sunspots within the error bars. One can see that the two SN reconstructions are consistent with each other, but with the ^{10}Be-based one being systematically higher, especially in the early part of the millennium. This is expected since Usoskin (2003) evaluated the upper limit of SN assuming the purely local production of ^{10}Be deposited in polar ice. Similar physics-based approach was used by Beer *et al.* (2003) who also reconstructed the solar activity on the multimillennia time scale using the ^{10}Be data from GISP2 core in Greenland. They did not reconstruct SN but presented the reconstructed modulation strength Φ skipping the last step in the physics-based model inversion, which may introduce additional uncertainties. The two reconstructions, based on ^{10}Be (Beer *et al.*, 2003 – these results are still preliminary) and on ^{14}C (Solanki *et al.*, 2004) data, are similar to each other (Jürg Beer, personal communication). Taking into account that the two models are independent and use different isotopes with different geochemical fate, this verifies the reliability of the long-term solar activity reconstruction.

4.3. VERIFICATION OF RECONSTRUCTION MODELS

As a verification of a SN reconstruction, its comparison with the actual GSN data for the last centuries is usually used. However, regression-based models cannot be tested in this way since this would require long set of independent direct data outside the "training" interval. It is usual to include all available data into the "training" period to increase the statistics of a regression, which rules out a possibility to test the model data. On the other hand, such a comparison to the actual GSN since 1610 can be regarded as a direct test for a physics-based model since it does not include phenomenological relation over the same interval (the only adjustable parameter in the model by Solanki *et al.* (2000) was fixed using data for 1975–2002). The period of the last four centuries is pretty good for the testing purpose since it includes the whole range of solar activity from nearly spotless Maunder minimum to the modern period of very active Sun. The agreement between the measured GSN and the ^{14}C-based reconstruction is excellent (the correlation coefficient $r = 0.93$ with the RMS deviation between the two series being 6) for the period 1610–1900 (Solanki *et al.*, 2004). The agreement between GSN and ^{10}Be-based reconstruction (Usoskin, 2003b) is also good ($r = 0.78$, RMS = 10 for 1700–1985). This validates the reliability of the physics-based reconstruction.

Note that both mathematical and physics-based models use an assumption on the constancy of involved processes over the studied time scale. However, they may change significantly through the ages. On the centuries-millennia time scale, the most important changes are long-term changes of the geomagnetic field, when both the geomagnetic dipole momentum changes and the dipole axis migrates (see, e.g., Hongre, 1998). These changes modify the global shielding from cosmic rays, changing thus the relation between SN and cosmogenic proxies. This may also distort interpretation of the frequency of aurorae watching in the past. While geomagnetic changes may distort the phenomenological reconstruction of sunspot activity from proxy data, the physics-based model can naturally account for the geomagnetic changes. Generally speaking, changes in the climate at the observational site may also affect the solar activity reconstruction. However, the global climate is known to be pretty stable during the Holocene (the present warm period lasting for about ten millennia).

5. Solar Activity on the Multimillennium Scale

Some features of the very long-term solar activity, such as the occurrence of grand minima, can be studied directly from cosmogenic isotope data, e.g., Voss (1996) and Peristykh and Damon (2003) analyzed the filtered Δ^{14}C data for the last millennia and demonstrated the existence of the secular (known also as Gleissberg) cycle and the 200–210-year (de Vries or Suess) cycle throughout the studied intervals. Also, a characteristic time of about 2000–2400 years was found in the frequency of grand minima occurrence (Vasiliev and Dergachev, 2002; Peristykh and Damon, 2003). Although this method is applied to an analysis of grand minima and qualitative behavior of solar activity, it cannot study the quantitative level of the activity. On the other hand, physics-based models (Section 4.2) provide quantitative reconstructions of solar activity which allow studying also long-term changes in the activity and, in particular, occurrence of periods with very high activity. The modern period of high solar activity with the average SN of about 76 after 1940 is known, from the direct observations, to be unique since 1610. Moreover, it was shown by Usoskin (2003b), who used a physics-based SN reconstruction from ^{10}Be data, that never during the last millennium was the Sun as active as it has been since 1940, while the cycle-averaged SN did not exceed the value of 50 for the millennium before that

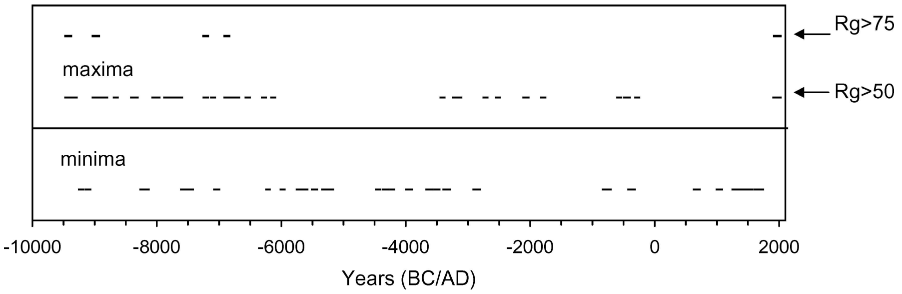

Figure 5. Periods of solar activity extremes according to the reconstruction by Solanki *et al.* (2004). *Lower panel*: grand minima, corresponding to reconstructed Rg < 10. *Upper panel*: periods of high activity, corresponding to reconstructed Rg > 50 and Rg > 75, as denoted in the right.

(see Figure 4). However, the multimillennia physics-based reconstruction using ^{14}C data (Solanki *et al.*, 2004) suggests that the present high-activity episode is not unique but rare on the multimillennia time scale, with several similar episodes appearing 8,000–10,000 years ago.

Figure 5 shows the periods of solar activity extremes. The lower panel depicts grand minima which are defined as periods when the reconstructed 10-year averaged SN did not exceed the value of 10 during at least 20 years. These periods are close to earlier reconstructions of grand minima periods (see, e.g., Figure 2 in Voss, 1996, who used raw $\Delta^{14}C$ data). The characteristic time of 2000–2400-year corresponding to clustering of grand minima is clear, while Gleissberg and de Vries (Suess) periodicities in the grand minima occurrence can be traced within the clusters. The most interesting is the upper panel of Figure 5 which shows the periods of high solar activity, according to the reconstruction by Solanki (2004), defined as a systematic (during at least 20 years) excess of SN over the given threshold level. Here we show active periods for the two threshold levels, 50 and 75. Periods when SN level exceeds 50 correspond to high solar activity. The latest (before the present one) such episode had happened about 2400 years ago, implying again that the modern episode is quite unique (SN level did not exceed 40 during the famous Medieval maximum in twelfth century). The total number of such episodes is about 30 although they are not uniformly distributed – they tend to cluster around 500 BC, 1500–3500 BC, and before 6000 BC. The threshold level of 75 corresponds to extremely high activity episodes. There are only five such extreme episodes (including the present one), four of which occurred before 6500 BC.

6. Concluding Remarks

We have presented a brief review of methods and results in studying long-term (from centennial to multimillennium time scales) solar activity which can be summarized as follows. Group sunspot numbers should be used instead of the Wolf series for the times before 1850. The use of a linear regression to reconstruct solar activity yields very uncertain results. Recently developed physics-based models raise solar activity reconstruction to the new level and allow studying its behavior on the multimillennia time scale. The frequency of the occurrence of extremes of solar activity is analyzed using SN reconstruction by Solanki *et al.* (2004). The characteristic time of 2000–2400-year as well as Gleissberg and de Vries (Suess) periodicities are apparent in the grand minima occurrence. It is important to note that the modern episode of very high solar activity (after 1940) is very rare in the multimillennia time scale, through the entire Holocene. There were only four other similar episodes, all of them occurred before 6500 BC.

We would like to see further investigations in the following directions. New measurements of cosmogenic proxies will help disentangle the terrestrial and solar signals. The physical models discussed here should be improved with more realistic consideration of changing geomagnetic and climatic factors. A systematic search for historical information on sunspot observation may resolve some uncertainties in sunspot activity during, e.g., the eighteenth century.

Acknowledgements

We thank Jürg Beer for useful discussions. We acknowledge financial support by the Academy of Finland. GAK was partly supported by the program "Nonstationary processes in Astronomy" of the Russian Academy of Sciences.

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