

Grand minima of solar activity during the last millennia

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Abstract. In this review we discuss the occurrence and statistical properties of Grand minima based on the available data covering the last millennia. In particular, we consider the historical record of sunspot numbers covering the last 400 years as well as records of cosmogenic isotopes in natural terrestrial archives, used to reconstruct solar activity for up to the last 11.5 millennia, i.e. throughout the Holocene. Using a reconstruction of solar activity from cosmogenic isotope data, we analyze statistics of the occurrence of Grand minima. We find that: the Sun spends about most of the time at moderate activity, $1/6$ in a Grand minimum and some time also in a Grand maximum state; Occurrence of Grand minima is not a result of long-term cyclic variations but is defined by stochastic/chaotic processes; There is a tendency for Grand minima to cluster with the recurrence rate of roughly 2000-3000 years, with a weak ≈ 210 -yr periodicity existing within the clusters. Grand minima occur of two different types: shorter than 100 years (Maunder-type) and long ≈ 150 years (Spörer-type). It is also discussed that solar cycles (most possibly not sunspots cycle) could exist during the Grand minima, perhaps with stretched length and asymmetric sunspot latitudinal distribution.

These results set new observational constraints on long-term solar and stellar dynamo models.

Keywords. Sun: activity, (Sun:) solar-terrestrial relations

1. Introduction

With the recent decline of overall solar activity, and in particular a very long and quiet minimum between solar cycles Nos. 23 and 24 in 2008–2010, the question of solar activity variability on longer timescales becomes acute (e.g., Schrijver *et al.* 2011). The recent solar cycle minimum appears unusual in many respects, e.g., in solar magnetic features (de Toma *et al.* 2010), in heliospheric modulation of cosmic rays (McDonald *et al.* 2010), in Space weather (Schwadron *et al.* 2010; Barnard *et al.* 2011). The last five solar cycles were very intensive corresponding to the unusual very active state of solar activity, or to a Grand maximum (Solanki *et al.* 2004; Usoskin 2008). Accidentally, the modern Grand maximum coincided with the space era with its numerous, precise and detailed in-situ and remote observation of the Sun, interplanetary medium and geosphere. Accordingly, the decline of solar activity after cycle No. 23 is often considered as an unusual phenomenon, probably leading to a Grand Maunder-like minimum. However, it is fully consistent with the features observed during the period of moderate solar activity in the 19-th century. Although a decline of the activity from the grand maximum state is apparent now, in accord with probabilistic predictions (Solanki *et al.* 2004; Abreu *et al.* 2008), it is unclear whether solar activity can slip into a new Grand minimum in the near future, or the Sun just returns to a moderate activity level, or possibly even returns into a Grand maximum

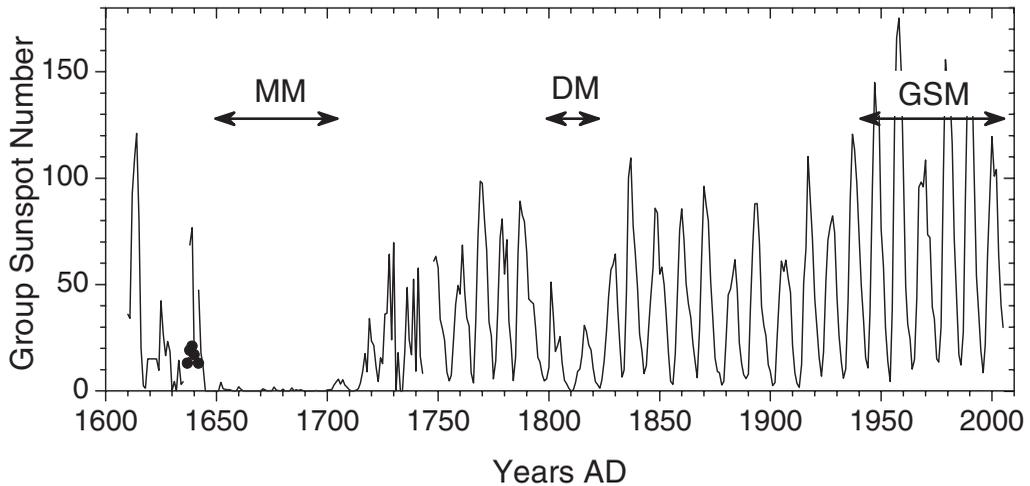


Figure 1. Monthly group sunspot numbers (Hoyt & Schatten 1998) since 1610. International sunspot numbers (Data Centre for the Sunspot Index (SIDC), Royal Observatory of Belgium, <http://sidc.oma.be/html/sunspot.html>) are used after 1996). Black dots represent newly revised sunspot numbers for years 1637–1641 (Vaquero *et al.* 2011). Maunder minimum (MM), Dalton minimum (DM) and the Grand Solar Maximum (GSM) are denoted.

state (e.g., Solanki & Krivova 2011). Therefore, a question of what is normal and what is unusual in the solar activity needs careful consideration, particularly with regard to minima of activity. This requires using a proxy of solar magnetic activity extending in the past, before the space era of direct measurements.

In this review we discuss the historical record of sunspot numbers for the last 400 years as well as solar activity on a time scale of a dozen millennia reconstructed from cosmogenic isotopes, as well as the method employed to obtain such activity records. We also put together general features of Grand minima of solar activity as deduced from solar activity reconstructed over the Holocene.

2. Solar activity over the last 400 years

For the last 400 years, solar activity is known pretty well in the form of the relative sunspot number (see details, e.g., in Usoskin 2008; Hathaway 2010). The sunspot number is based on original or reproduced drawings and records of sunspots observed by professional or amateur astronomers. Initially introduced by Rudolf Wolf of Zürich in the 19-th century as the relative sunspot number (also known as Wolf sunspot number), it was greatly improved to the group sunspot number series by Hoyt & Schatten (1998) to take its present form (Fig. 1). Still some new records and drawing continue to be found in archives, making further corrections of the sunspot series possible (e.g. Vaquero 2007; Arlt 2008; Vaquero *et al.* 2011), but the main pattern is quite well established.

- The main feature is the 11-year quasi-periodical solar cycle (known as the Schwabe cycle), produced by the solar dynamo (Hathaway 2010).
- The magnitude of the Schwabe cycle (observed as the envelope) varies greatly on the centennial time scale.
- It includes the Maunder minimum in 1645–1715 (Eddy 1976; Soon & Yaskell 2003) when almost no sunspots were present, and the Dalton minimum at the turn of 18-th to the 19-th centuries.

- Between the 1940s and 2000s, the level of activity was high, exceeding 100 in the peak sunspot number. This period corresponds to the modern Grand solar maximum (Usoskin *et al.* 2003; Solanki *et al.* 2004).
- The length of the Schwabe cycle also varies, being between about 8 and 14 years. It is weakly anti-correlated with the cycle magnitude (Dicke 1978; Hoyng 1993; Solanki *et al.* 2002; Hathaway 2010).

Thus, the sunspot record suggests that solar activity is more often at a moderate level (peak sunspot numbers between 50 and 100), but may display excursions to the very quiet state of a Grand minimum (Maunder minimum) or very active state of a Grand maximum. The Dalton minimum is not considered as a complete Grand minimum but rather as a separate state of the dynamo (Schüssler *et al.* 1997), or an unsuccessful attempt at reaching a Grand minimum (Sokoloff 2004).

The sunspot series is one of the longest regular scientific observations and forms a benchmark for many studies, related, e.g., to solar/stellar physics, solar-terrestrial relations and geophysics. Therefore, the question arises of how representative is the sunspot series for the last 400 years for solar activity on much longer time scales? Are the last 400 years a typical period or special in some way? In order to study solar activity variations in the past, before the start of regular (instrumental) sunspot observations, one has to use more indirect proxies of solar activity. Since such proxies as naked-eye observations of sunspots and aurorae borealis recorded in historical chronicles, cannot be used for quantitative studies (Usoskin 2008), the best way to reconstruct past solar activity is related to naturally archived proxies as discussed in the next section.

3. Solar activity proxy: Cosmogenic isotopes

The magnetic Sun forms the heliosphere – a region of about 200 AU across, totally controlled by the permanently emitted solar wind and frozen-in heliospheric magnetic field (HMF). The dynamic heliosphere is driven by the solar activity (solar wind velocity and density, HMF strength, coronal mass ejections, etc.) and, in turn, modulates the influx of galactic cosmic rays (GCR) observed near Earth (e.g., Scherer *et al.* 2006). Energetic particles of GCR, when entering the Earth's atmosphere, collide with nuclei of atmospheric gases, producing, in particular, radioactive nuclides. Some of them, which have no terrestrial sources except cosmic rays, are called cosmogenic isotopes, and their amount is defined by the GCR flux modulated by solar magnetic activity and an additional geomagnetic shielding. The amount of cosmogenic nuclides can be measured in natural archives and used to reconstruct solar activity in the past, provided the geomagnetic field can be independently reconstructed (see, e.g., Beer 2000; Usoskin 2008). The main advantage of this method is its *off-line* type: natural archival records in independently datable samples (ice cores, stratified sediments, or tree trunks) can be measured nowadays in modern laboratories. As a result, a homogeneous, i.e. of roughly equal quality for different times, data series can be obtained for further analysis.

Most important for the long-term reconstruction of solar/heliospheric activity are two nuclides - radiocarbon ^{14}C and ^{10}Be . Details of their production, transport and archiving are given below.

Radiocarbon ^{14}C (half-life 5730 years) is produced as a result of capture of an atmospheric thermal neutron by a ^{14}N nuclei: $^{14}\text{N} + n \rightarrow ^{14}\text{C} + p$. It is produced mostly in the upper troposphere – low stratosphere (Masarik & Beer 2009). Once produced it gets oxidized to CO_2 and, in gaseous form, takes part in the global carbon cycle (see Fig. 2), whereby it gets completely mixed in the atmosphere. As the ocean with its huge

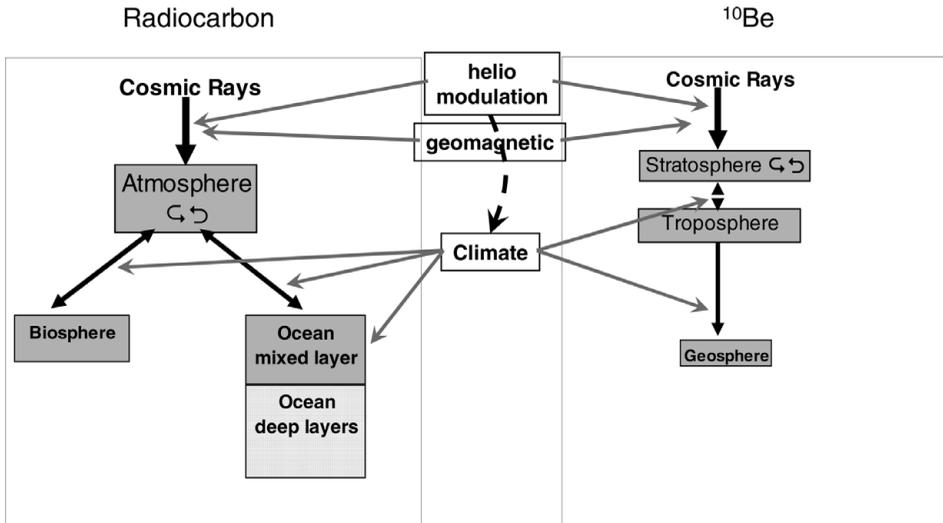


Figure 2. A cartoon showing production and redistribution of cosmogenic isotopes ^{14}C (Radiocarbon, left panel) and ^{10}Be (right panel). The flux of GCR is affected by both the heliospheric modulation and the geomagnetic field. ^{14}C is globally mixed in the atmosphere and within different reservoirs, including the deep and mixed ocean layers, and finally stored in the biosphere (living plants). Climate changes can affect the ^{14}C concentrations via slow changes of the ocean circulation/ventilation, which can play a role on millennial time scales. ^{10}Be is sufficiently mixed in the stratosphere but quickly precipitates from the troposphere. The processes of atmospheric redistribution/precipitation can be severely affected by regional atmospheric dynamics.

capacity and slow response is involved in the carbon cycle, the ^{14}C production changes are damped in magnitude (e.g., by a factor of 100 for the Schwabe cycle and delayed (see, e.g., Siegenthaler *et al.* 1980; Bard *et al.* 1997). However, if the ocean and atmospheric circulation remain roughly constant, as can be validated for the Holocene (Stuiver *et al.* 1991), the carbon cycle can be effectively reduced to a simple Fourier filter (Usoskin & Kromer 2005). Due to the global carbon cycle, ^{14}C is not sensitive to fast regional climate changes, but may be affected by slow trends in the ocean circulation. Production of ^{14}C in the 20-th century is very difficult to study, because of the fossil fuel burning (Suess effect), which inhomogeneously dilutes natural radiocarbon with a large amount of ^{14}C -free CO_2 (Tans *et al.* 1979).

Measurements of the $\Delta^{14}\text{C}$ (normalized ratio $^{14}\text{C}/^{12}\text{C}$ – see, e.g. Damon & Sonett 1991) are done on samples of tree-trunks, where annual tree rings allow absolute dating. As a result, a calibration ^{14}C curve for the last 25 millennia is available (Stuiver *et al.* 1998; Reimer *et al.* 2004) presenting the global ^{14}C signal.

Isotope ^{10}Be (half-life $1.36 \cdot 10^6$ years) is produced in spallation of atmospheric N, O and Ar nuclei by cosmic rays, mainly in the lower stratosphere – upper troposphere (Kovaltsov & Usoskin 2010). It soon gets attached to atmospheric aerosols and thus descends relatively quick. Its residence time in the stratosphere is a few years (Beer 2000) leading to partial mixing. The tropospheric residence time is a few weeks. Concentration of ^{10}Be is usually measured in polar (Greenland or Antarctic) ice cores, allowing for independent dating by glaciological methods. Deposition of ^{10}Be is straightforward, with the dominant precipitation at mid-latitudes and relatively small deposition in polar regions (Field *et al.* 2006; Heikkilä *et al.* 2009). However, it is affectable by the atmospheric circulation and precipitation pattern, and thus the ^{10}Be signal in ice cores can be greatly affected by the regional climate (precipitation), particularly on temporal scales shorter than 100

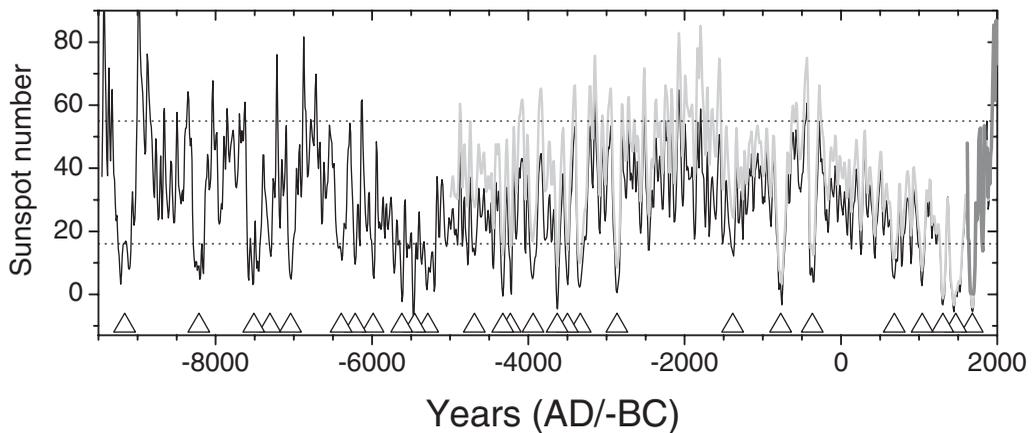


Figure 3. Reconstruction of the decadal (thus, the 11-yr solar cycle is not visible) solar sunspot activity over the Holocene, based on ^{14}C data (Solanki *et al.* 2004; Usoskin *et al.* 2006, 2007). The black and blue curves are built using the paleomagnetic reconstruction by Yang *et al.* (2000) and Korte & Constable (2005), respectively. The thick red curve is the actually measured group sunspot numbers (Hoyt & Schatten 1998). Horizontal dotted lines roughly indicate the levels chosen for Grand minima and maxima. Blue triangles depict centers of the identified Grand minima (Usoskin *et al.* 2007).

years. Presently there is no global ^{10}Be series, and the data are related to individual ice cores which may be prone to local/regional climate variability, whose influence is difficult to estimate.

Because of very different redistributions of the two isotopes in the geosphere, a common signal in their records can be robustly ascribed to the production, viz. solar or geomagnetic, signal. A detailed comparisons between the two isotopes (Bard *et al.* 1997; Usoskin *et al.* 2009a) shows that they agree with each other at time scales between 100 and 1000 year. The ^{14}C data are in good agreement with Antarctic Dom Fuji (Horiuchi *et al.* 2008) and Greenland GISP (Finkel & Nishiizumi 1997) ^{10}Be series, while South Pole (Bard *et al.* 1997) and Greenland Dye-3 (Beer *et al.* 1990) ^{10}Be series yield poor correlation with other data sets. On longer time scales, a systematic discrepancy is observed in the early Holocene (cf. Vonmoos *et al.* 2006), that is probably related to the delayed effect of the deglaciation. The lack of agreement on the short time scale (< 100 years) is likely related to the regional climate (depositional pattern) influence on ^{10}Be content in ice cores and/or to possible dating errors of the ice cores. It is interesting that the pair-wise agreement between ^{14}C and any of the ^{10}Be series is better than between the individual ^{10}Be series, confirming an essential role of the local/regional climate on individual ice core ^{10}Be records. Thus, redistribution of the isotopes in the geosphere, which is to a large extent unknown in the past, may distort the production (viz. solar activity) signal in the record. Polar records of ^{10}Be are prone to short-term regional and long-term global transport variability. Radiocarbon is insensitive to short-term climate changes but can be affected by changes in the large-scale ocean circulation at multi-millennial scales. In order to resolve these uncertainties, a combined result from different proxy records is needed.

4. Solar variability and Grand minima during the past millennia

A reconstruction of solar activity, based on the ^{14}C global INTCAL record, is shown in Fig. 3 for the Holocene, as made using the method by Solanki *et al.* (2004) Usoskin *et al.*

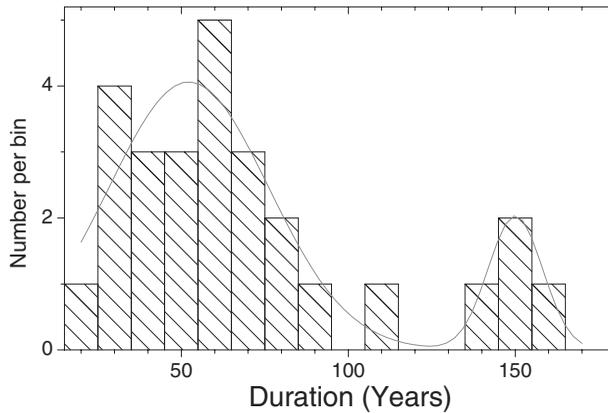


Figure 4. A histogram of the duration of the reconstructed Grand minima (modified after Usoskin *et al.* 2007) along with the best-fit double Gaussian. A clear bimodality, corresponding to Maunder- and Spörer-type minima, can be observed.

(2007) and paleomagnetic reconstructions by Yang *et al.* (2000) and Korte & Constable (2005). Long-term variations of the geomagnetic field, which provides additional shielding for GCR at Earth, are evaluated independently by paleomagnetic methods (Donadini *et al.* 2010). Uncertainties in the paleomagnetic data form the main source of the solar activity reconstructions (Solanki *et al.* 2004; Snowball & Muscheler 2007). One can see from Fig. 3 that using different paleomagnetic data one obtains slightly different overall levels of the reconstructed activity. However, the definition of Grand minima, which form the primary focus of this paper, is quite robust, so that the properties of the identified Grand minima are hardly affected by this uncertainty.

In our recent work (Usoskin *et al.* 2007) we have defined Grand minima of solar activity as periods when the (smoothed) sunspot number is ≤ 15 during at least 20 years or forms a clear dip (the depth ≥ 20 with respect to the surrounding level) with the bottom being ≤ 20 in sunspot numbers. This definition is more robust, as it accounts for possible uncertainties, than a simple threshold definition (e.g., Stuiver *et al.* 1991; Voss *et al.* 1996; Abreu *et al.* 2008). In this way, 27 Grand minima have been identified during the Holocene (see Table 1 in Usoskin *et al.* 2007), with the total duration of about 1900 years, thus about $1/6$ of the total time. This list largely agrees with other lists of Grand minima (Eddy 1977; Stuiver & Braziunas 1989; Goslar 2003). We note that Abreu *et al.* (2008) defined Grand minima and maxima differently, as the lowest and uppermost 20% of the reconstructed activity, respectively.

It has been shown that Grand minima present a special state of the dynamo rather than being simply fluctuations of the dynamo parameters (Moss *et al.* 2008). Grand minima tend to appear in clusters with roughly 2400 years separation (the Hallstatt cycle, see e.g., Damon & Sonett 1991). Within the clusters, the Grand minima appear with roughly 210-year quasi-periodicity (de Vries or Suess cycle, see e.g., Suess 1980).

4.1. Duration and recurrence of Grand minima

The duration of the Grand minima has a bimodal distribution (see Fig. 4), with shorter Maunder-like (100 years or shorter) and longer Spörer-like (about 150 years) minima (Stuiver & Braziunas 1989; Goslar 2003; Usoskin *et al.* 2007). The two peaks corresponding to these different types of Grand minima are highly significantly distinguishable.

The time intervals (waiting times) between consequent Grand minima are more consistent with a power-law than with an exponential distribution (Usoskin *et al.* 2007).

This feature, observable as clustering of the Grand minima, suggests that the occurrence of Grand minima can be governed by non-Poissonic processes (e.g., self-organized criticality, de Carvalho & Prado 2000) with the presence of an intrinsic long-term memory. However, a thorough statistical analysis (Usoskin *et al.* 2009c) shows that, because of the insufficient number of events (Grand minima), the null hypothesis of the purely Poisson (stochastic) process with an exponential distribution of the waiting times cannot be ruled out. Thus, the result of a non-Poissonic nature of Grand minima occurrence is only barely significant (confidence level 0.93).

4.2. Solar cycle during Grand minima

Although the level of the surface magnetic activity drops below the sunspot formation threshold during a Grand minimum, different data sets imply that the global solar dynamo is not completely switched off but keeps operating, although in a special mode. An analysis of sunspot and aurora (Křivský & Pejml 1988) data suggests that the dominant periodicity of the solar cycle during the Maunder minimum was ≈ 22 years rather than the usual 11-year Schwabe cycle (Silverman 1992; Usoskin *et al.* 2001). An analysis of ^{14}C data also indicates longer cycles during the Maunder minimum (Peristykh & Damon 1998; Miyahara *et al.* 2004). Another Grand minimum not covered by sunspot observations, the Spörer minimum in the turn of 15–16-th centuries, is also characterized by extended cycles according to the ^{14}C data (Miyahara *et al.* 2006).

Results based on ^{10}Be data are less clear. Only Greenland ice cores, e.g. Dye-3 (Beer *et al.* 1990) and NGRIP (Berggren *et al.* 2009), provide sufficient resolution to study solar cycles. Although a band-pass filtered Dye-3 data depicts a weak 10-year cycle during the Maunder minimum (Beer *et al.* 1998), it has incorrect (*in phase*) relation with direct manifestations of solar activity (Usoskin *et al.* 2001). On the other hand, a wavelet or spectral-time analysis of both Dye-3 and NGRIP data sets yields a 15–20-year dominant periodicity (which is however, statistically insignificant) of ^{10}Be data during the Maunder minimum, in agreement with other proxies, and a 4–8-year intermittent variability, likely related to the regional North-Atlantic climate variability mode.

4.3. North-South asymmetry

Direct solar observations suggest that sunspot formation was highly asymmetric during the Maunder minimum, with sunspots observed mostly in the south hemisphere (Ribes & Nesme-Ribes 1993; Sokoloff 2004). Newly reconstructed and analyzed data (Arlt 2008) made it possible to reconstruct sunspot positions for the beginning of the Dalton minimum, which also show a significant asymmetry but with the northern hemisphere now being dominant (Usoskin *et al.* 2009b). This does not support the idea of a relic solar magnetic field weakly affecting the sunspot activity (Cowling 1945; Sonett 1983; Mursula *et al.* 2001). The north-south asymmetry (when one hemisphere dominates over the other) seems to be a feature of a Grand minimum, although this observation is based on only two known examples.

4.4. General scenario of a Grand minimum

The question on whether the onset of a Grand minimum is sudden or gradual is not fully clear. A widely accepted paradigm, schematically shown in Fig. 5, assumes that a Grand minimum begins suddenly, without apparent precursors, following normal activity cycles (Usoskin 2008). Recovery of the activity level from the deep minimum to normal activity is gradual, via emergence of the 11-year cycle. The transition may take several decades. This scenario puts an important constraint on the solar dynamo theory as, e.g.,

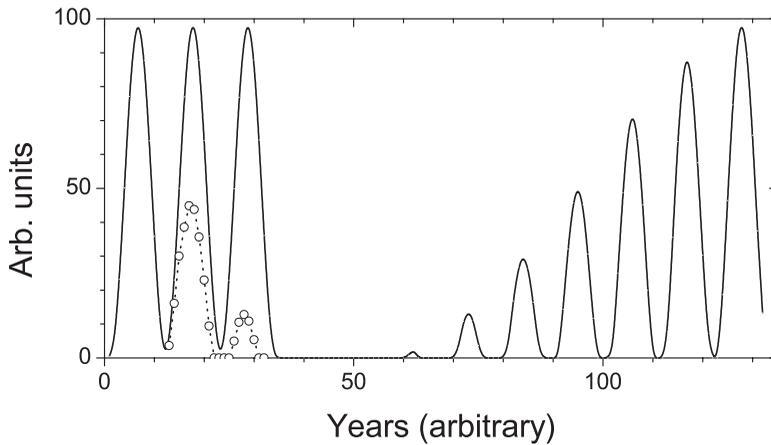


Figure 5. A schematic general scenario of sunspot activity around a Grand minimum (solid curve): sudden termination of active cycles to the very deep minimum followed by a gradual recovery. However, a scenario with a gradual decline of activity (dotted curve) may be more likely on the basis of recent evidence (Vaquero *et al.* 2011). This plot does not represent any particular Grand minimum.

it is consistent with some dynamo models (Charbonneau 2001), but disagree with the others.

However, such a scenario is mostly based on the Maunder minimum and hence suffers from very poor statistical significance. In addition, a recent re-analysis of historical sunspot records by Vaquero *et al.* (2011) yields that a couple of solar cycles before the Maunder minimum were low, suggesting a gradual beginning of the Grand minimum (dotted curve in Fig. 5). Also, there are some indications, based on high resolution ^{10}Be and ^{14}C data, that the length of the solar cycle may be slightly stretched a few cycles before the onset of a Grand minimum (Fligge *et al.* 1999; Miyahara *et al.* 2010). However, this idea is also based on only two examples, Maunder and Spörer minima.

5. Summary

Solar magnetic activity as reconstructed using direct sunspot observations for the last 400 years and cosmogenic isotopes (^{14}C and ^{10}Be) proxy data for millennia, depicts a great deal of variability on different time scales, from the dynamo-driven 11-year Schwabe solar cycle to the centennial and millennial variability. The level of solar activity varies from a quiet Grand minimum with virtually no sunspots on the solar disc to a Grand maximum characterized by the very active Sun.

In this paper we do not aim at providing an overview of all aspects of long-term solar activity but rather focus on Grand minima. The main features of the Grand minima can be summarized as follows (features, marked with the * sign, are based on one or a few examples only and cannot be considered as statistically grounded):

- The Sun spends about $3/4$ of the time at moderate activity, $1/6$ in the Grand minimum and about $1/10$ in the Grand maximum state (depending on the selection criterion).
- Identification of Grand minima is robust and is not grossly affected by the uncertainties of the paleomagnetic data.
- Occurrence of Grand minima is not a result of long-term cyclic variations but is defined by stochastic or chaotic processes.
- There is a tendency for Grand minima to cluster with the recurrence of roughly

2000-3000 years. Within clusters, a ≈ 210 -yr quasi-periodicity (de Vries or Suess cycle) exists between Grand minima.

- Grand minima occur of two different types: short (≤ 100 year) Maunder-type and long (about 150 years) Spörer-type minima.
- Solar cyclic dynamo keeps operating during Grand minima, but at a greatly reduced strength and perhaps with stretched cycle length.
- The presently available data somewhat favors gradual onset of a Grand minima.
- Sunspot activity can be strongly asymmetric between northern and southern hemispheres during a Grand minimum.

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Discussion

LEIF SVALGAARD: There is general acceptance that the heliospheric open flux now is similar to 110 years ago. Therefore, shouldn't the modulation of cosmic rays be the same as 110 years ago?

ILYA USOSKIN: Despite some indirect open flux reconstructions, cosmic rays are known to be less modulated 100 years than now, as confirmed by cosmogenic isotopes, ^{10}Be in the polar ice and ^{44}Ti in meteorites.

ARNAB CHOUDHURI: (Comment) You pointed out that the statistics for grand maximum were consistent with fluctuations, but grand minimum statistics were more complicated. I think this is because there is a different mechanism needed for recovery from grand minimum (different from fluctuations), which could complicate the statistics.

ILYA USOSKIN: I am glad you can immediately interpret our results.

JEFFREY LINSKY: (Comment) Another physical concept that should be considered with regard to cosmic ray interpretation, the Sun is moving through the in-homogeneous interstellar medium. The size of the heliosphere varies depending on the structure of this medium. We move at 1 parsec/300000 years and the size of the heliosphere is much smaller than 1 parsec. The interstellar medium may change density by significant factors (2, 8, 10).

ILYA USOSKIN: I agree such fluctuations may exist on very long-term scale but they are expected to be small for high-energy cosmic rays because of the diffusion length.