Variations in Solar Activity Across the Spörer Minimum Based on Radiocarbon in Danish Oak

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Abstract Several aspects concerning the origin and nature of grand solar minima remain unclear, and more high-resolution 10Be and 14C records are needed to improve our understanding of these phenomena. Here, we report 137 new high-precision, annually resolved radiocarbon concentrations based on oak from the Danish dendrochronology. The new record covers a period (CE 1432–1578) that encompasses most of the penultimate grand solar minima known as the Spörer Minimum. A detailed comparison between the Spörer and Maunder (CE 1640–1720) minima shows that the Spörer Minimum is associated with enhanced Δ14C variability in a band centered around the 11-year Schwabe cycle from CE 1450 to 1479 and between CE 1545 and 1578, whereas little 11-year variability is observed from CE 1479 to 1539. In contrast, we only observe enhanced 11-year variability after the end of the Maunder Minimum at CE 1722–1744, which could indicate that the nature and origin of the two minima were different.

1. Introduction

The Sun displays cyclic behavior related to changes in magnetic activity. Observations of sunspots and magnetic field strengths show that the dominant change in magnetic activity is associated with the so-called Schwabe cycle characterized by an average period of 11 years. A complete cycle of polarity changes of the solar magnetic field, known as the Hale cycle, spans two Schwabe cycles and lasts around 22 years. The Sun also changes on longer timescales, and during the Maunder Minimum (MM, CE 1640–1720) and the Spörer Minimum (SM, CE 1390–1550) the solar magnetic activity was lower than usual over several consecutive magnetic cycles (Eddy, 1976). Historical records of sunspots, aurorae, and the solar corona show this for the MM (Eddy, 1976). Such observations are, however, very sparse during the SM as it occurred before the invention of the telescope. Evidence for grand solar minima (GSMs) prior to CE 1610 therefore mostly relies on cosmogenic nuclides in terrestrial archives, such as 10Be in ice cores and 14C in tree rings. Cosmogenic nuclides are produced by spallation reactions (10Be) and neutron capture (14C) when galactic cosmic rays from space penetrate Earth's atmosphere. The production rates of cosmogenic nuclides are inversely correlated with solar magnetic activity due to the nonlinear shielding effect of the solar magnetic field. Eddy (1976) noted that the deviation from normal levels in atmospheric 14C was greater during the peak of the MM than during the peak of the SM, but the SM lasted longer than the MM, indicating that there may be two separate kinds of GSM, a Spörer kind and a Maunder kind of GSM (Usokin, 2007).

Since the early work by Eddy (1976), new high-resolution 10Be and 14C records have increased our understanding of past solar activity, but several aspects remain unclear. In order to gain a better understanding of solar activity, it is necessary to investigate the occurrence rates, duration, and depth of these grand minima (and the related grand maxima). Since historical sightings only cover one GSM (as well as the smaller Dalton Minimum around CE 1797–1828), it is essential to obtain reliable, high-precision radiocarbon records across several minima to investigate their similarities and differences. A detailed comparison between the two most recent GSM, including the transition into and out of the minima, will help form a more coherent theory of the solar dynamo. For instance, it is unclear what exactly characterize GSMs and if different types of minima, such as the Spörer kind and the Maunder kind, exist. It is also unknown whether or not...
GSMs represent low-amplitude extensions of the regular solar dynamo rather than intermittencies, where the solar dynamo undergoes a sudden shift to a quiescent state (Charbonneau, 2010). In the latter case, it is possible that different kinds of quiescent states or dynamo modes exist (Moss et al., 2008).

The relationship between the 11-year Schwabe cycle and GSMs also remains uncertain. We know that the Sun was devoid of sunspots during the deepest part of the MM (1645–1715), but this does not imply that the 11-year Schwabe cycle ceased to exist during the MM, because sunspots represent a threshold phenomenon that are produced when the strength of the magnetic field in the active regions exceeds 1,500 Gauss (Livingston et al., 2012). It is possible that the 11-year solar cycle continued to modulate the atmospheric production of $^{14}$C and $^{10}$Be throughout the minimum, but the magnetic fields associated with the active regions were too weak to produce sunspots. The underlying hypothesis is that if the 11-year Schwabe cycle can be detected in $^{10}$Be and $^{14}$C records spanning the GSM, it is likely that GSMs represent a low-amplitude extension of the solar dynamo. It is notoriously difficult, however, to study the 11-year Schwabe cycle during GSMs, in part because variations in atmospheric $\Delta^{14}$C associated with the 11-year cycle are comparable to the precision of the individual radiocarbon measurements. Estimates of the $\Delta^{14}$C variability associated with the Schwabe cycle range from 2‰ (Stuiver & Braziunas, 1993) to 4‰ (Baroni et al., 2011). Beryllium-10 data from ice cores are often influenced by local climatic noise, but band-pass filtered $^{10}$Be data from the NGRIP core indicate that the 11-year Schwabe cycle persisted during the MM and SM (Beer et al., 1998; Berggren et al., 2009).

Stuiver (1993) and Stuiver & Braziunas (1993, updated in 1998) reported annual radiocarbon ages for the period CE 1510–1954, covering the MM and part of the SM. They did not find appreciable differences in the magnitude of oscillations in a 5- to 20-year band-pass-filtered signal during the MM and before and after this interval. Miyahara et al. (2004) published annual $^{14}$C measurements and found the Schwabe cycle to lengthen to 13–15 years during the MM with a corresponding lengthening of the Hale cycle to 24–29 years. They found a weakening of the cycle at the onset of the minimum around CE 1640–1665. Miyahara et al. (2006, 2007, 2008, 2010) furthermore made annual or biannual $^{14}$C measurements of the SM and the years immediately before and after this GSM. They found the Schwabe cycle to lengthen between CE 1390 and 1430, and then to shorten to have 11-year periodicity between CE 1430 and 1455. Between 1460 and 1480, Miyahara et al. (2008) once again found a slight stretching and weakening of the Schwabe cycle. The years from CE 1455 to 1510 were characterized by the largest suppression of 11-year solar variability, but the 11-year cycle increased in strength, albeit slightly, between CE 1510 and 1540. Around CE 1550–1570, the periodicity of the Schwabe cycle shortened once again according to Miyahara et al. (2007). Sakamoto et al. (2017) also reported annual radiocarbon measurements from Japan between CE 1545 and 1610, but they did not study the presence of cyclicities in the data. All these annual Japanese records found a slight offset between their data sets and the data of Stuiver et al. (1998) or the IntCal13 curve (Reimer et al., 2013), but it is likely due to upwelling of radiocarbon-depleted water masses near Japan (Nakamura et al., 2013). Recently, Eastoe et al. (2019) reported annual radiocarbon measurements from California, USA, between CE 998 and 1510. They found some cyclicities with periods near 7 years in an interval from CE 1320 to 1450 but otherwise did not report any periodicities during the SM. Usoskin et al. (2016) reported the duration and center years for 20 GSMs based on sunspot numbers reconstructed from cosmogenic isotopes, which changed the estimated duration and timing of the SM to CE 1390–1550 as opposed to the timing used by Eddy (1976; CE 1460–1550).

Here, we present 137 new, high-precision annual radiocarbon ages for the period CE 1432–1578 based on oak from the Danish dendrochronology. These data constitute the first European annual $^{14}$C record covering most of the SM along with circa 30 years after the minimum itself. By comparing this new record with the annual record of Stuiver et al. (1998) spanning the MM, we analyze similarities and differences in the $\Delta^{14}$C variability associated with these two GSMs and investigate potential solar-cycle-induced changes during the minima.

2. Methods

Two archeological samples of oak, Gr02 (Eriksen, 1995) and SchB (Eriksen, 1996), from Southern Jutland, Denmark, were dendrochronologically dated using the program DENDRO for Windows (Tyers, 1999) with methods outlined by Baillie and Pilcher (1973). The samples were cut using a thin blade into annual samples of early wood and late wood (see supporting information for more details on the dating and cutting).
We only used late wood since it is the most reliable component for tracing past variations in atmospheric radiocarbon (Fogtmann-Schulz et al., 2017; Kudsk et al., 2018; McDonald et al., 2019). We only used the α-cellulose fraction, as this is the most stable part of the wood (Nemec et al., 2010). By following the procedure of Loader et al. (1997), the α-cellulose was extracted by delignification with sodium chlorite (NaClO₂) and acetic acid (CH₃COOH), and subsequent removal of hemicelluloses with sodium hydroxide (NaOH). Afterward, samples were again washed with sodium chlorite (NaClO₂) and acetic acid (CH₃COOH). The α-cellulose was combusted to CO₂ in sealed glass tubes containing copper oxide (CuO) and then graphitized following the procedure of Olsen et al. (2017). The radiocarbon fraction was measured with a 1-MV HVE Tandetron Accelerator Mass Spectrometry (AMS) system at the Aarhus AMS Centre at Aarhus University. The measured 14C/12C ratios are corrected for isotopic fractionation by using the online AMS 13C/12C ratio normalized to a standard δ13C value of −25‰ Vienna Pee Dee Belemnite (Stuiver & Polach, 1977). The resulting radiocarbon ages are reported as conventional 14C dates in 14C years BP. Age-corrected Δ14C values are calculated according to Stuiver and Polach (1977) and Jull et al. (2014).

We measured a total of 271 samples (see Table S3 and Figure S4). This included 83 annual samples from SchB (CE 1432–1525) and 136 annual samples from Gr02 (CE 1432–1578). In order to test the robustness of the enhanced variability observed during some parts of the time series, we additionally measured 21 samples from Gr02 between CE 1481 and 1509 (approximately annual) and 24 samples from Gr02 between CE 1526 and 1578 (approximately biannual). In order to test our performance over time, every wheel of samples (eight) measured in the AMS contained a sample from CE 1469 Gr02. The weighted mean of these eight measurements resulted in a Δ14C value of 12.07 ± 0.86‰, which passed the χ² test (χ²: 1.5 ≤ 2.0) and implies the age of this ring can be reproduced within the quoted uncertainties.

Samples from the same year were combined by calculating the weighted mean, provided the samples passed a reduced χ² test (Bevington & Robinson, 2003). In 12 cases, where the samples marginally failed the χ² test, the uncertainty was increased by multiplying it with the square root of the χ² value, see, for example, samples from CE 1434 (see Table S3 in the supporting information), whereas samples clearly failing the χ² test were removed as outliers. Sample years with only one measurement were χ² tested using the previous and succeeding year and removed as outliers if the χ² test failed. This resulted in 137 annual 14C data points.

In order to visually enhance signals potentially associated with the solar cycle, the data were smoothed using a low-pass filter with a cutoff at 5 years. To remove any long-term variability from the data set, a moving-mean filter of 30 years was subtracted from the data. The periodicities in the data set were investigated by calculating a power spectrum using REDFIT (Schulz & Mudelsee, 2002), which uses a Lomb-Scargle Fourier transform. The advantage of this procedure over wavelet analysis is that data with gaps, such as missing years, can be readily analyzed. The variance in different frequency bands was furthermore investigated by using band-pass filters with a stopband attenuation of 60 dB.

3. Results

The average precision of the individual measurements is 20.0 14C years BP or 2.2‰, whereas the average precision of the combined new Danish data set (Figure 1) is 16.7 14C years BP or 2.1‰. Overall, our new data set follows the IntCal13 curve (Reimer et al., 2013) but shows more fine structure, since the IntCal13 curve is based on decadal averages. There are 57 overlapping years between our new data set and the data set of Stuiver et al. (1998; CE 1510–1578) with an average difference of (0.34 ± 0.34)‰. Of the 57 overlapping years, 53 of them show no significant differences based on a reduced χ² test. A χ² test (χ²: 1.05 ≤ 1.33) of the entire data sets further shows that the two records are not statistically different, which enhances the validity of both data sets and indicates that the uncertainties are not underestimated.

Figure 1. The annual Δ14C values found in this study as well as other annual values covering the same time interval and the IntCal13 curve (Reimer et al., 2013). The blue band shows the low-pass-filtered data. AARAMS = Aarhus Accelerator Mass Spectrometry Centre.
Figure 2. Band-pass-filtered data in different bands confined by the periods on the right. Blue (a, b and c) is our annual data; red (d, e and f) is the annual data of Stuiver et al. (1998). The light blue and light red boxes mark the duration and the dashed black line the center year of the Spörer Minimum and Maunder Minimum according the timing from Usoskin et al. (2016).

The annual data set of Miyahara et al. (2006, 2007) was also compared to our annual data set, with 129 common years between the two data sets. There is a systematic offset of $1.35 \pm 0.33\%$, meaning the data of Miyahara et al. (2006, 2007) are an average of $10.7 \pm 2.6^{14}C$ years BP older than our data. Despite this offset, 120 of the 129 common years show statistical agreement (passed a $\chi^2$ test). The observed offset is likely explained by upwelling of radiocarbon-depleted water masses near Japan (Nakamura et al., 2013). A similar comparison between our annual data set and the MEISJ-1 data set of Sakamoto et al. (2017) shows that the $\Delta^{14}C$ values of MEISJ-1 are generally lower by $4.53 \pm 0.65\%$ than our new record from Danish oak. This corresponds to radiocarbon ages that on average are $36.1 \pm 5.2^{14}C$ years BP older than the new record from Danish oak. A $\chi^2$ test of the 25 overlapping years shows that the two data sets are statistically different ($\chi^2: 2.04 \leq 1.52$). Again, this offset is likely explained by upwelling since the MEISJ-1 data are also based on Japanese wood (Nakamura et al., 2013). A comparison between our annual data set and the annual data set of Eastoe et al. (2019) shows a mean difference of $1.22 \pm 0.30\%$ between the 79 common years. This means that their data on average are $9.68 \pm 2.37^{14}C$ years BP older than our data. These two records are overall statistically different ($\chi^2: 1.67 \leq 1.28$), but 67 of the 79 common years show statistical agreement (passed a $\chi^2$ test).

In order to investigate the $^{14}C$ variability associated with the SM, the data were band-pass filtered (Figure 2). In the band-pass filter from 3 to 7.6 years (Figure 2a), we observe no clear changes throughout the investigated time period, but there are some distinct, short-lived variations around CE 1445 and 1530 characterized by large peak-to-peak amplitudes of $\sim 9-11\%$. The general peak-to-peak variations in the 3- to 7.6-year period band are between 3\% and 5\%. In a band centered on the 11-year Schwabe cycle (8–16 years; Figure 2b), the amplitude of the peak-to-peak variations ranges between 3.3\% and 3.9\% until CE 1479. Hereafter, the amplitude is dampened for an extended period until CE 1539, at which point the variability in the 8- to 16-year period band increases again with maximum values around 5.6\%. The time interval characterized by dampened variability appears after the center year of the GSM (CE 1470 (Usoskin et al., 2016)), indicating that the SM was not symmetric around the center year, or that the timing of the sunspot minimum and the radiocarbon maximum was not fully aligned. A similar pattern is observed for the band centered on the 22-year Hale cycle (16–35 years; Figure 2c), where an interval characterized by low-amplitude variability (CE 1500–1513) is bounded by intervals displaying larger variability.
Figure 3. Amplitude spectra (a and c) and time-resolved periodograms (b and d) of our data (CE 1432–1578; a and b) and the data of Stuiver et al. (1998, 1630–1790; c and d). The first and last 25 years are missing in the periodograms due to a window size of 50 years. A 30-year running mean filter has been subtracted from the data. The blue vertical lines on (b) and (d) mark the center year and the black vertical lines mark the end of the grand solar minima, according to the timing from Usoskin et al. (2016). The dashed vertical lines mark periods of 11 and 22 years.

A spectral analysis of our annual Δ14C data shows a period of 24.5 years above 99% false-alarm level (Figure 3a). The analysis moreover indicates three peaks corresponding to periods between 6.5 and 8.9 years above 90% significance consistent with the periodicities found by Eastoe et al. (2019) near 7 years. A time-resolved periodogram (Figure 3b) shows the 22-year Hale cycle to be present throughout most of the SM and that the period is elongated between CE 1490 and 1530. There is no sign of the 11-year Schwabe cycle at the 90% false-alarm level until CE 1545, where it appears with a shortened period of 8–9 years.

4. Discussion

We have plotted our annual data spanning the SM together with the annual data of Stuiver et al. (1998) covering the MM along with the low-pass-filtered data for both data sets to compare the two GSMs (Figure 4). The center year (defined by Usoskin et al., 2016) of each GSM appears to early by ~15 years for both minima when compared to the midpoint of the peak anomalies in Δ14C. The sunspot number during the MM was zero, or close to zero, in CE 1645–1714, but the maximum in radiocarbon lasts longer and reaches the maximum peak value between CE 1700 and 1716, so the timing of the sunspot minimum and the radiocarbon maximum is not fully aligned. There is a clear difference between the two grand minima; the MM is shorter and has a narrower peak compared to the SM that is characterized by a flat, more elongated peak. Both curves rise until CE 1460 and CE 1670, respectively. Hereafter, the Δ14C values during the SM is not rising until the end of this plateau, whereas the Δ14C values during the MM continue to rise.

Spectral analysis of the Δ14C data does not show significant (90% confidence level) 11-year cyclicity during the two grand minima (Figure 3). Potential periodicities in the data of Stuiver et al. (1998) from CE 1630–1790 are furthermore investigated using the band-pass filters that were used for the Spörer data (Figure 2). As was the case with the Spörer data, there is no apparent change of amplitude during the investigated interval in the band from 3 to 7.6 years (Figure 2d), but the peak-to-peak amplitude, typically ranging between 2‰ and 4.5‰, is smaller in the record covering the MM. The low degree of high-frequency variability associated
with the MM reflects the low degree of year-to-year scatter. Variations in the band centered on the 11-year Schwabe cycle (8–16 years; Figure 2e) are relatively small until CE 1722, at which point the amplitude increases, indicating that the Schwabe cycle became stronger when the sunspot minimum ended. However, the 11-year variability is larger from CE 1660 onward than before the onset of the MM until 1660, in contrast with our analysis of the SM. In the band centered on the 22-year Hale cycle (16–35 years; Figure 2f), on the other hand, the amplitude is large before and in the beginning of the minimum until CE 1693, where the amplitude drops. Peristykh and Damon (1998) also investigated the annual record of Stuiver et al. (1998) and found the 11-year Schwabe cycle to have higher amplitudes after the MM than before, consistent with our findings. However, they found the 22-year Hale cycle to have higher amplitudes after the MM, but their intervals were different than ours, implying that the results are not fully comparable. The robustness of these comparisons between amplitude variations in different frequency bands is generally challenged by low signal-to-noise ratios. Variations around the Schwabe and Hale cycles are, however, more robust than the higher-frequency variations, which are more sensitive to the influence of stochastic noise.

Miyahara et al. (2004) found the 11-year Schwabe cycle to be elongated and strongly attenuated from CE 1640–1665, consistent with our findings. However, they found the amplitude of the 22-year Hale cycle to rise around CE 1695, which is in contrast with our findings, which suggest a decrease around CE 1690. Miyahara et al. (2008) observed a slight attenuation of the 11-year Schwabe cycle during CE 1460–1480, which is earlier than in the Spörer record based on Danish oak. From CE 1495 to 1510, the Schwabe cycle in the Japanese record is nonexistent (Miyahara et al., 2006), consistent with our findings. The 22-year Hale cycle was found to have an amplitude less than 1% until CE 1520, contrary to our findings suggesting a Hale cycle with a higher amplitude until CE 1499. At CE 1550–1570, Miyahara et al. (2007) observed a shortening of the Schwabe cycle, which we also see in our new record taking place already in CE 1545.

5. Conclusion

We present 137 new, high-precision annual radiocarbon concentrations for the period CE 1432–1578 based on Danish oak. The record is generally in agreement with annual records of Stuiver et al. (1998) and Miyahara et al. (2006, 2007). Detailed comparison with annual radiocarbon ages from Stuiver et al. (1998) covering the MM shows that the MM is shorter and has a narrower peak than the SM, which is characterized by a flatter, more elongated peak as expected from the IntCal13 curve (Reimer et al., 2013). The solar variability in a band centered around the 11-year Schwabe cycle is most suppressed between CE 1479 and 1539, after the center year of the minimum based on reconstructions of sunspot numbers (Usoskin et al., 2016). Band-pass-filtered data centered on the 11-year cycle show enhanced variability around the end of the minimum and the following years for both GSMs. For the MM, this period coincides with the reappearance of sunspots on the solar surface. The fact that we observe similar enhancements in the variability in band-pass-filtered records centered on the Schwabe cycle toward the end of the SM indicates that this feature might be a general feature of GSMs. We are, however, not able to investigate if the Sun was capable of generating sunspots during this period as very limited historical sunspot observations exist from this period. Indications of a similar behavior are observed in a band-pass-filtered record centered on the 22-year Hale cycle, that is, that it seems to die out during the deepest parts of the minima. Also, the fact that we only see enhanced variability in a band-pass-filtered record centered on the 11-year Schwabe cycle during the beginning of the SM and not the MM indicates that the enhanced variability is not a general feature of GSMs, or that the nature of the SM and MM is different.

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Figure 4. Our annual samples and the annual samples of Stuiver et al. (1998). The light red and light blue boxes mark the duration and the dashed black line mark the center year of the Maunder Minimum and Spörer Minimum, respectively, according to the timing from Usoskin et al. (2016).
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