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Variation of solar activity during the grand solar minima deduced from radiocarbon content in tree rings

H. Miyahara[a], K. Masuda[a], H. Menjo[a], K. Kuwana[a], Y. Muraki[a] and T. Nakamura[b]
(a) Solar-Terrestrial Environment Laboratory, Nagoya University, Aichi 464-8601, Japan
(b) Center for Chronological Research, Nagoya University, Aichi 464-8601, Japan
Presenter: K. Masuda (kmasuda@stelab.nagoya-u.ac.jp), jap-masuda-K-abs1-sh34-oral

The variations of solar activity during the Maunder and Spoerer Minima were deduced from the measurements of ^{14}C concentration in tree rings. The "eleven-year" cycle was lengthened to be about fourteen years during the Maunder Minimum but that during the Spoerer Minimum did not change. We investigate the features of the "eleven-year" and "twenty-two year" variations of the ^{14}C content. The ^{14}C records show remarkable "twenty-two year" structure, which may be due to cyclic magnetic reversal of the Sun. The variation of ^{14}C content suggests that the polarity of the Sun was negative when the Maunder Minimum started.

1. Introduction

Cosmogenic nuclides are produced in the earth's atmosphere mainly by the galactic cosmic rays (GCRs) coming from outside of the heliosphere. On the way to the earth, GCRs are modulated by the solar wind and the interplanetary magnetic field. The GCRs interact with the earth's atmosphere and produce showers of secondary particles that in turn produce cosmogenic nuclides. Cosmogenic nuclides preserved in stratified ice cores or in tree rings can provide sequences of the indices of solar activity, state of the interplanetary magnetic field and the flux of the GCRs, which are extendable to the past when observational records are not available. Generally, intense solar activity results in a decrease of production rate of cosmogenic nuclides while weakening of solar activity brings an increase. Radiocarbon (^{14}C), which is one of the cosmogenic nuclides, is produced by the neutron capture of nitrogen nuclei and is absorbed into tree rings by photosynthesis after circulating in the carbon cycle as a form of CO_2.

In a recent paper [1], we have investigated the features of solar cycle during the Maunder Minimum, which is the period of prolonged sunspot minima from 1645 AD to 1715 AD, by measuring the ^{14}C content in the Japanese cedar tree with annual time resolution. The sunspot activity has shown scarcely the cyclic structure for this period. However, the frequency analysis of the ^{14}C record has shown significantly the period of about 13-15 years together with the period of about 23-29 years, which suggests the persistent cyclic magnetic reversals of the Sun through the Maunder Minimum with the period several years longer than that of recent solar activity.

In this paper, we investigate more detailed features of the "eleven-year" and the "twenty-two year" variation of ^{14}C content and examine the correlation with the sunspot activity. It has been suggested that the flux of GCRs is relatively higher for the negative solar polarity than that for the positive polarity, during the prolonged solar activity minimum [2]. Based on this idea, we examined the transition of solar polarity during the Maunder and Spoerer Minima.

2. Measurement

The samples were Japanese cedar trees (*Cryptomeria japonica*), one from the Yaku Island in southern Japan for the Spoerer Minimum and one from Murouji-temple in central Japan for the Maunder Minimum. The year of growth was determined by measuring the bomb peak of the ^{14}C content. The age of the rings was

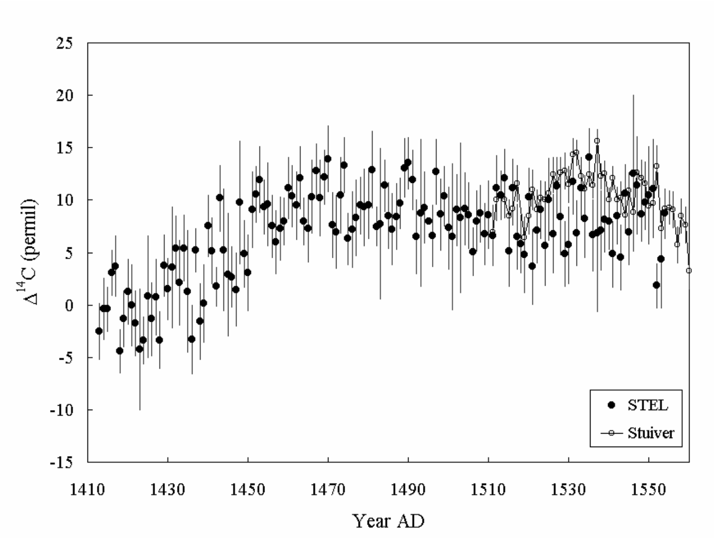

Figure 1 (a) Records of ^{14}C content in tree rings from 1413 AD to 1553 AD including the Spoerer Minimum. Black dots are ^{14}C data obtained by our group with annual time resolution. Open squares show the annual ^{14}C data obtained by Stuiver et al. [3].

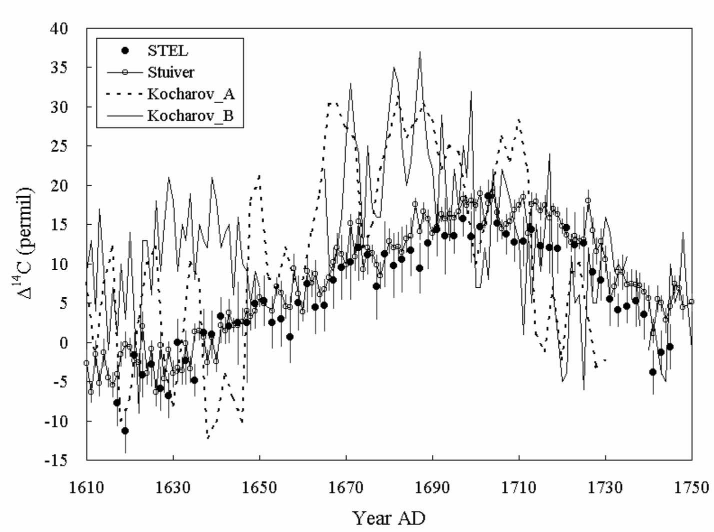

Figure 1 (b) Records of ^{14}C content in tree rings from 1617 AD to 1745 AD including the Maunder Minimum. Black dots are ^{14}C data obtained by our group with bi-annual time resolution. Open circles show the annual ^{14}C data obtained by Stuiver et al. [3]. Broken line and solid line are two series of ^{14}C data by Kocharov et al. [4].

also confirmed dendrochronologically. Annual tree ring samples, corresponding to the periods of the Spoerer Minimum and the Maunder Minimum, were cut out from the blocks. Cellulose component of wood was extracted and then graphite was produced for measurement of ^{14}C concentration with an accelerator mass spectrometer at Nagoya University. A typical measurement error is 0.3 %.

The measured result of ^{14}C content for the Spoerer Minimum is shown in fig. 1 (a). The period of our measured data overlapped that of Stuiver's [3] from 1510 AD to 1550 AD. Although absolute values of ^{14}C content are slightly different between our data and Stuiver's, variation of ^{14}C content is similar in both records.

For the Maunder Minimum we have slightly extended our previous record of ^{14}C to a period from 1617 AD to 1745 AD. The data were taken every other year with annual time resolution. Figure 1 (b) shows the result together with the annual ^{14}C data obtained by Stuiver et al. [3] and two series of the data by Kocharov et al. [4]. Our data agree with those of Stuiver within the measurement errors. Kocharov's data show large amplitude variation compared to both of our result and Stuiver's.

3. Discussion

In order to extract the "eleven-year" and "twenty-two year" variations in ^{14}C records for the Maunder Minimum, the data were treated with band-pass filters with the bandwidths of 10-18 years (Fig. 2 (a)) and 10-35 years (Fig. 2 (b)). Values of $\Delta^{14}C$ in both figures are plotted in inverse scale. The group sunspot number is also shown for comparison. Time lag between the production of ^{14}C in the atmosphere and the absorption into trees has been taken into account. We assumed that the time lag is three years.

It is evident from the ^{14}C records in Fig. 2 (a) that the GCRs had retained cyclic variation through the Maunder Minimum with almost constant amplitude, even though such significant variation is not seen in the sunspot record. As is suggested by the spectral analysis of ^{14}C records, the cycle seems to be lengthened only during the Maunder Minimum. In consequence, it can be concluded that the number of the solar cycle during the seventy years from 1645 AD to 1715 AD was no more than five.

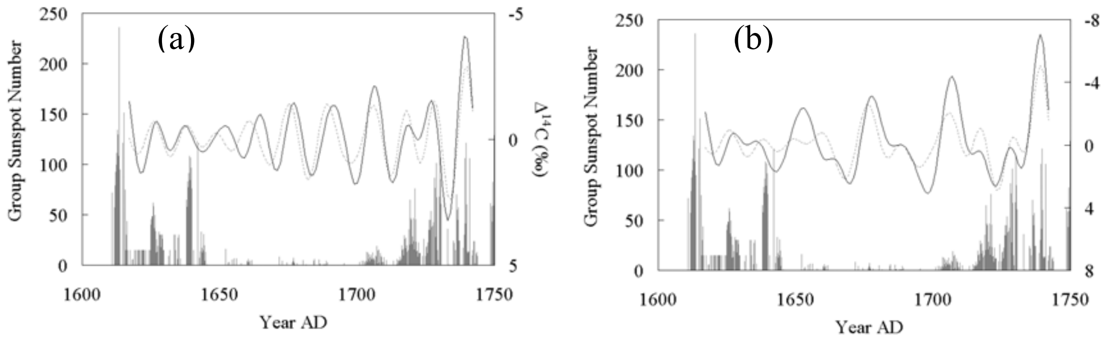

Figure 2. Monthly group sunspot activity and the band-pass filtered carbon-14 records with the bandwidth of (a) 10-18 years and (b) 10-35 years. Note that the carbon-14 data are plotted inversely. The time-lag of 3 years in the carbon cycle has been also taken into account. The solid curve shows the band-pass filtered carbon-14 data obtained by this study (dots in Figure 1), and the dotted curve shows the band-pass filtered carbon-14 data (circles in Figure 1) obtained by Stuiver et al. (1998).

Figure 2 (b) exhibits the features of the "twenty-two-year" variation of ^{14}C, which can be caused by the modulation of the GCRs depending on solar magnetic polarity [2]. It can be recognized that the "twenty-two year" cycle is also lengthened in association with the lengthened "eleven-year" cycle. It has been suggested that the flux of the GCRs is relatively higher for negative solar magnetic polarity during the Maunder Minimum [2]. The periods of high concentration, appearing at around 1645 AD, 1670 AD and 1700 AD might correspond to the period when solar magnetic polarity is negative. So the Maunder Minimum started at negative polarity of solar magnetic field at around 1645.

Such an appearance of the twenty-two year cycle is also recognizable in the variation of ^{14}C content during the Spoerer Minimum (1415-1534 AD) as shown in Fig. 3. The "twenty-two year" structure is seen as the suppression of every other peak (1480 AD, 1500 AD, 1525 AD), which may also suggest the periods of solar magnetic polarity positive.

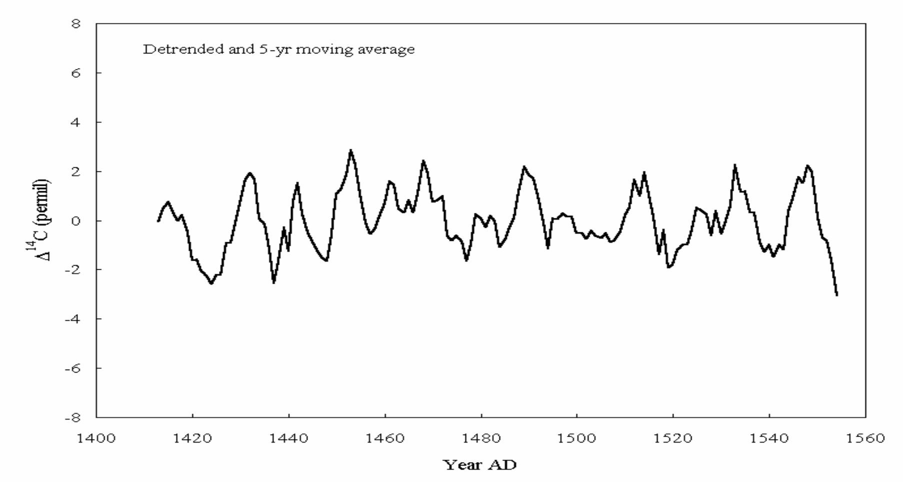

Figure 3. Annual radiocarbon content expressed in $\Delta^{14}C$ (permil) from the Spoerer minimum after detrended and 5-yr moving averaged.

4. Conclusions

In the ^{14}C records both for the Maunder and Spoerer minima, "twenty-two year" cyclic structure was detected. It suggests that the Sun had retained the polarity reversal through the prolonged sunspot minimum period. By analyzing the detailed variation of the twenty-two year cycle in ^{14}C content, it is possible to determine the polarity of the solar magnetic field in the past when the direct observational records are no longer available.

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