

VARIATION OF THE RADIOCARBON CONTENT IN TREE RINGS DURING THE SPOERER MINIMUM

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ABSTRACT. This paper presents the variation of radiocarbon content in annual tree rings for the period AD 1413–1553, which includes the Spoerer Minimum period (AD 1415–1534). Since the variation of the production rate of ^{14}C is strongly related to solar activity, the variation of ^{14}C content in annual tree rings gives us information on the characteristics of variation of solar activity. We have studied solar activity during the grand solar minima, focusing especially on the stability of the 11-yr cycle. The minima are determined to have been almost free of sunspots. Our results, however, have revealed quite remarkably the existence of the 11-yr cycle for most of the time during the Spoerer Minimum. The 11-yr variation weakened around AD 1460–1510, suggesting that solar activity might have been strongly suppressed during these 50 yr.

INTRODUCTION

Continuous sunspot data are available only after the beginning of the 18th century (Figure 1), immediately following the Maunder Minimum, when the sunspots had almost disappeared and the earth's temperature was lower than usual by 1 to 2 °C. Since then, the sun appears to have followed the "11-yr" cycle rather constantly. However, most of the history of the solar cycle is still unclear and the constancy of its period is a matter of controversy, especially during the period of grand solar minima.

The history of solar activity can be investigated by measuring the abundance of cosmogenic nuclides in layered natural archives such as trees or ice cores. Cosmogenic nuclides such as radiocarbon are mainly produced by incoming galactic cosmic rays (GCR) which are modulated by the solar wind and interplanetary magnetic field. When the sun is active, the flux of incoming GCR decreases, and consequently, the production rate of cosmogenic nuclides decreases, and vice versa. Therefore, the production rate of the cosmogenic nuclides has an anti-correlation with solar activity. ^{14}C produced in the upper atmosphere forms carbon dioxide which circulates within the atmosphere and some is absorbed into tree rings.

About 10,000 yr of decadal data on the ^{14}C content of the atmosphere are available so far. On the other hand, continuous annual ^{14}C data, required to investigate the solar cycle in detail, are available only for the period from AD 1511–1945. Figure 2 shows the decadal variation of the ^{14}C content in tree rings from the 11th century (Stuiver et al. 1998). Decadal-to-centennial variations are mainly caused by the variation of solar activity. Periods of high concentration correspond to the grand solar minima, and it is likely that there were 5 grand minima during the last millennium. The second most recent ^{14}C maximum is the Maunder Minimum, for which sunspot data are available (Figure 1). Prior to this was the Spoerer Minimum, for which neither sunspot data nor annual data of ^{14}C concentration have so far been obtained. We have aimed to measure the ^{14}C content annually in tree rings during the Spoerer Minimum, and have studied the corresponding solar variations, focusing especially on the change of the 11-yr cycle. We have now almost completed measuring all of the annual samples for the Spoerer Minimum. Here, we report the results of the measurement and discuss the characteristics of the variation of ^{14}C concentration during the Spoerer Minimum.

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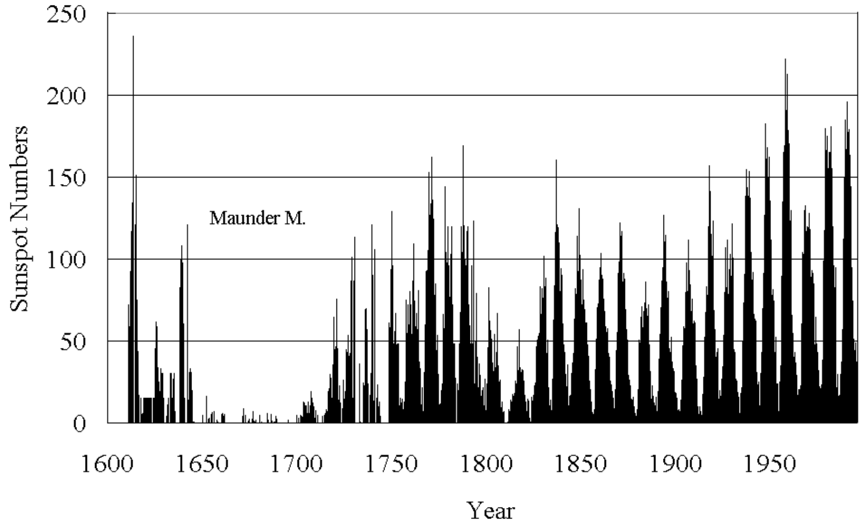

Figure 1 Sunspot numbers from the 17th century (Hoyt and Schatten 1998)

MEASUREMENT

To study the variation of ^{14}C content during the Spoerer Minimum, a 711-yr-old Japanese cedar tree, obtained at 30.18°N, 130.30°E, was used. The tree rings were first dendro-dated and separated annually, and then milled into small pieces. Each piece was then washed with a benzene-ethyl alcohol mixture to remove resins and other constituents which could move between rings. The extracts were subsequently bleached by a $NaClO_2$/HCl solution at 80 °C to remove lignin. They were then boiled and rinsed in distilled water. The resultant celluloses were combusted with CuO to obtain CO_2 gas. After purification, the CO_2 gas was deoxidized to graphite using H_2 gas (Kitagawa et al. 1993). Finally, the samples were pressed into the target holders of the accelerator mass spectrometer (AMS). The concentration of ^{14}C in each graphite sample was measured by using the AMS of Nagoya University in Japan, which achieves an accuracy of 3–5‰.

RESULTS AND DISCUSSION

Figure 3 shows the ^{14}C content in the tree rings from AD 1413 to 1553. The margin of error includes statistical error for ^{14}C counting and the stability of the AMS system. The solid curve is the decadal data shown in Figure 2. Our results are consistent with this curve. Our data, however, reveal more detailed variations that may be caused by solar variations. First, data gaps were replaced using a linear interpolation and the time series was analyzed for periodicity. The power spectrum of the Fourier analysis showed peaks at the periods around 5, 7, 11, and 22 yr. The peak at 11 yr was most prominent, its confidence level being about 2.3 σ. On the other hand, the 22-yr period, which can be considered as the Hale cycle, was relatively insignificant and comparable to the statistical uncertainty. It is notable that the 11-yr Schwabe cycle remained the most dominant during the Spoerer Minimum, although solar activity is considered to have been extremely low and sunspots almost absent at that time.

Next, the data were analyzed by band-pass filtering in order to remove the high frequency noise and the long-term trend. Figure 4 shows the detailed variation of amplitude of the 11-yr Schwabe cycle which was derived from the data with a filter with a bandwidth of 10–12 yr. In the beginning of the

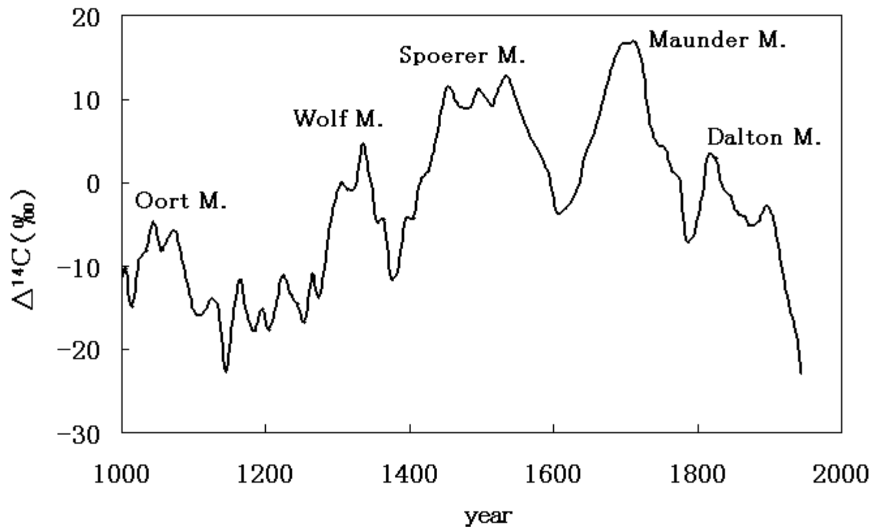

Figure 2 Decadal variation of ^{14}C content in tree rings (Stuiver et al. 1998)

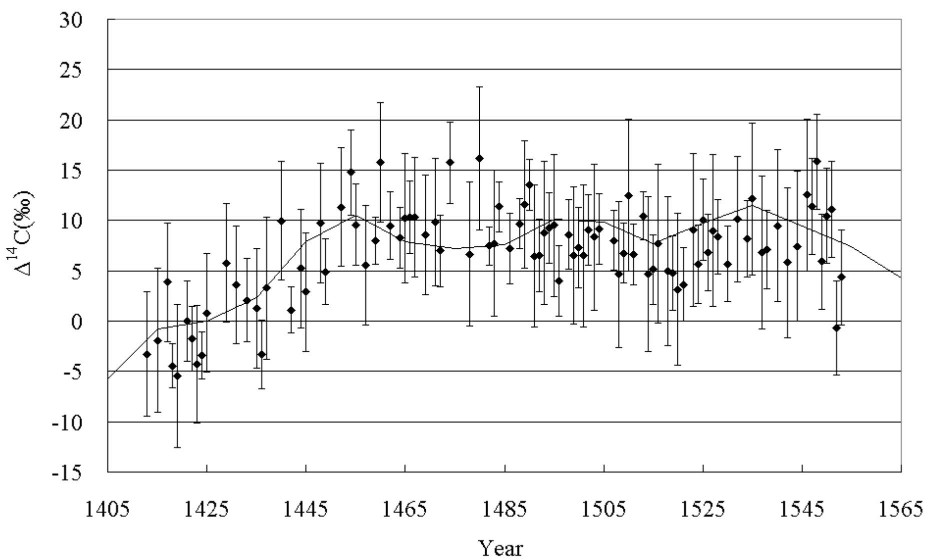

Figure 3 The ^{14}C content in tree rings during the Spoerer Minimum

period, the amplitude of the 11-yr cycle was about 1.5‰ and appeared to be weak around AD 1460–1510. From around AD 1510, the 11-yr Schwabe cycle seems to have recovered, increasing to about 1.5‰. The cosmic ray flux usually varies by 15–20% through a solar cycle with a corresponding variation of the ^{14}C content of the atmosphere of about 1.5–2.0‰, which is consistent with our result. As for the period of AD 1460–1510, when the 11-yr cycle was weak, it appears that the solar activity might have been most absent.

The data were also analyzed using the wavelet transform method in order to investigate more detailed variations of the periodicity. As a result, we found that there is a possibility that the 11-yr

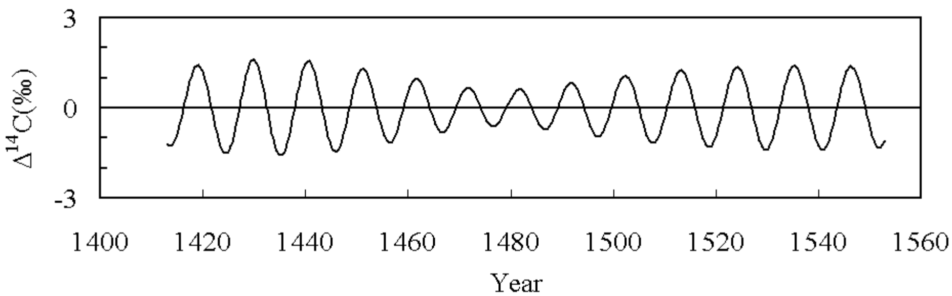

Figure 4 Variation of the amplitude of 11-yr period

Schwabe cycle was stretched by several years during the period when the 11-yr cycle was suppressed. As is well known from sunspot data, the length of the Schwabe cycle and the intensity of solar activity have an anti-correlation (Clough 1905; Baliunas and Soon 1995). This also supports the view that the sun was very quiet during the middle 50 yr of the Spoerer Minimum. The same feature of a lengthened and weakened 11-yr cycle has been also reported for the Maunder Minimum (Peristykh and Damon 1998). This feature might be common to solar activity during the grand minima, though our data for the Spoerer Minimum is as yet incomplete and can be improved. We also have already begun measurements relevant to the Maunder Minimum using a Japanese cedar tree. These comparisons will bring us more information on the characteristics of solar variations during the grand minima.

CONCLUSION

The variation of solar activity during the Spoerer Minimum has been surveyed by measuring the ^{14}C content in annual tree rings. As a result, the existence of the 11-yr cycle with an amplitude around 1.5‰ has been confirmed in the variation of ^{14}C concentration in the beginning and in the end of the Spoerer Minimum. The 11-yr cycle was suppressed around the middle 50 yr of the minimum. During this period, solar activity appears to have been most weakened, and the 11-yr cycle might have been stretched by several years. This feature is similar to that found in the Maunder Minimum. Further measurements will clarify the features of solar activity during these minima in greater detail.

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