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Solar activity variation in grand solar minima deduced from cosmogenic radiocarbon

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Abstract: The sun is variable in its magnetic activity with various time scales of 11-year Schwabe cycle and longer cycles. In grand solar minima such as the Maunder Minimum (1645-1715 AD), sunspots were almost absent and the solar activity was very weak. Solar activity variation affects the intensity of galactic cosmic rays entering earth's atmosphere and therefore production rate of cosmogenic isotopes. Radiocarbon is one of the cosmogenic isotopes and variation of its content reflects the change of the solar activity. We found the length of the Schwabe cycle in the Maunder Minimum deduced from the radiocarbon content was longer than 11-year. On the other hand, the Schwabe cycle length in the Spoerer Minimum (1416-1534 AD), which is considered to be another grand solar minimum, was almost 11-year. In order to investigate whether the variability of the solar cycle length is related to the long-term variation such as grand solar minima, we have measured annual radiocarbon content in extended periods in the last 1200 years. Based on the result, we will discuss the difference in solar cycle length for solar grand minima.

Introduction

The sun is variable in its magnetic activity with 11-year Schwabe cycle and in the reversal of magnetic polarity with 22-year Hale cycle. These cyclic variations of solar activity and hence changes of the solar wind properties and the interplanetary magnetic field modulate the energy spectrum and intensity of galactic cosmic rays (GCR) entering the heliosphere and the terrestrial circumstances. The cosmic rays entering the upper atmosphere interact with atmospheric nuclei and produce secondary particles and also some isotopes. Radiocarbon (^{14}C) is one of those cosmogenic isotopes, whose half-life is 5,730 years. Radiocarbons are created mainly by a process that atmospheric nitrogen nucleus captures a secondary neutron produced by cosmic ray interaction and emits a proton. Production rate of this terrestrial radiocarbon in the atmosphere changes with the same periodicity as that of the cosmic ray intensity. Produced radiocarbon forms carbon dioxide CO_2 and circulates in the terrestrial environment together with stable carbon isotopes. On the way of the carbon cycle, some of carbon dioxides are taken into trees by photosynthesis and the carbon is fixed in annual rings. The tree rings are a good archive which preserves the concentration of radiocarbons in stratified layers. The variation of radiocarbon concentration in tree rings reflects the change of cosmic ray intensity and solar activity in the period when the tree rings were formed although the amplitudes of variations are reduced depending on the cycle length.

Solar activity can be known by observation of sunspot number as an index. However, it is not possible to know the solar activity from sunspots for the solar activity minima such as the Maunder Minimum when the sunspots were almost absent. Before 1600 AD when telescope was invented, there had been no reliable observation of sunspots.

Therefore, ^{14}C is the best tool to investigate the solar activity in the past. We have investigated characteristics of the Schwabe cycle and the Hale cycle of the solar activity in the past measuring the variation of ^{14}C concentration in annual tree rings for the last 1,200 years although the entire period was not covered. In this paper, we present the results of our measurements on ^{14}C concentration in annual tree rings and compare the cyclicity in the several periods, featured as grand solar minima or normal activity periods.

Table 1: Features of sample trees

Tree	Place	Geo-graphical location	Period of growth
A	Yaku	30.3°N 130.5°E	97-1956 AD
B	Yaku	30.3°N 130.5°E	1280-1991 AD
C	Murou-ji	34.5°N 136.0°E	1617-1998 AD

Method

We have used three different trees, which are designated as trees A, B and C. They are all Japanese cedar (*Cryptomeria japonica*). Trees A and B grew at Yaku Island in southern Japan. The geographical location is 30.3°N, 130.5°E. Tree A was cut down in 1956 and the age was 1,860 years old or more. Tree B was cut down in 1991 and the age was 712 years old. Tree C was obtained from Murouji-temple in central Japan. The geographical location is 34.5°N, 136.0°E. This tree fell by a strong typhoon in 1998 and the age was 382 years old. The years of growth of these trees were determined by measurement of the bomb peak of the ^{14}C content in 1964 and/or by dendrochronological analysis. Information on the sample trees are listed in table 1. Annual tree ring samples were cut off from the blocks. Cellulose component of wood was extracted chemically and then graphite was produced through CO_2. The ^{14}C concentration was measured by using an accelerator mass spectrometer at Nagoya University. A typical measurement accuracy was 0.3 %. Details of sample preparation and measurement are mentioned elsewhere [1, 2].

Results and Discussion

Reimer et al. [3] compiled the data of decadal ^{14}C contents for more than 10,000 years and the dataset is called INTCAL04. Figure 1 shows a part of INTCAL04 for the last 1,400 years, together with annual data of our measurements and Damon's result [4]. The properties of the Schwabe and the Hale cycles for each period are summarized as followings.

The Maunder Minimum (1645-1715 AD)

In a previous paper [1], we investigated the features of solar cycle during the Maunder Minimum, which is the period of prolonged sunspot minima, by measuring the ^{14}C content in tree C with annual time resolution. The sunspot activity has shown scarcely the cyclic structure for this period because of absence of sunspots. However, the frequency analysis of the ^{14}C record showed a periodic behavior with the period of 13-15 years together with the period of 23-29 years. This result suggests the persistent cyclic magnetic activity and reversals of the solar magnetic polarity throughout the Maunder Minimum with the period several years longer than those of recent solar activity, with an exception that the Schwabe cycle was somewhat suppressed between 1640 to 1665 AD.

The Spoerer Minimum (1416-1534 AD)

There exists another peak of ^{14}C content around 1500 AD. This period is usually considered to be one of the solar activity minima, called the Spoerer Minimum. We measured annual ^{14}C content in tree B for this period. According to the frequency analysis, however, periods of the Schwabe/Hale cycles were kept at 11 years and 22 years [2]. The amplitude of 11-year cycle was weakened in 1455 to 1510 AD while that of 22 years stayed almost constant.

The Interval between the two minima

The solar activity in the interval between the two minima is considered to be normal or even high. In addition to the data of the two minima, the 14C contents in annual rings of tree B in this interval were measured. The result shows rather short cyclic behavior, that is, 11 years or even 10 years for the Schwabe cycle and 22 years for the Hale cycle.

Now the time series of ^{14}C content for 333 years from 1413 to 1745 AD is available and displayed in fig. 2. The variation of ^{14}C concentration is filtered with 8-35 years in this figure for clarification of the 11-year and 22-year variations.

The period of 9th to 11th century

In order to confirm the variation of Schwabe cycle in the periods of normal solar activity or even high solar activity, we have measured 14C content in tree A through 9th to 11th century. The terms, for which the 14C content was measured, are the period of 880 to 964 AD (10th century) and that of 992 to 1072 AD (11th century). Frequency analysis of the 10th century data shows that there are 10-year and 17-year periodicities around 930 to 950 AD while these cyclicity is weak around 900 to 920 AD, when the 14C variation shows a small peak with a width of 40 years, possibly being a solar activity minimum.

The period of 992 to 1072 AD corresponds to early half of the Oort Minimum, which is assigned as one of solar activity minima. Damon et al. [4] measured 14C content from 1065 to 1150 AD, which is the latter half of the Oort Minimum. If we combine these data, the property of the Oort Minimum can be discussed. Our frequency analysis through the Oort Minimum indicates that the 10-year and 22-year periodicities are seen and 10 year periodicity was suppressed or lengthened to 12 years around the deepest period (1050-1080 AD).

Conclusions

We have measured ^{14}C concentrations in annual tree rings for the last 1200 years. The periodicities of the Schwabe and Hale cycles were investigated in association with the long-term variation of solar activity. the results are summarized in table 2. The periods of the Schwabe and Hale cycles in the Maunder Minimum were about 14 years and 28 years, showing prolonged periodicity compared to the recent 11 and 22 years. However, those in the Spoerer Minimum seem to be the same as those in the present time although the 11-year cyclicity was suppressed to some extent in the main term of the minimum. In other periods such as 9th to 11th century and interval of the minima, the periodicities were almost the same as or even shorter than that in the present time. The periodicity of the Schwabe and Hale cycles might be dependent on the extent of long-term variation of solar activity. Measurements for various periods are necessary to clarify the dependency.

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Table 2: Comparison of cyclicity of solar activity in various periods

Period	Periodicity (years)		Suppression of cycle
	Schwabe Cycle	Hale Cycle	
small minimum + normal period (880-964 AD)	10	17	Yes (weak)
normal period (992-1072 AD) + Damon (Oort Minimum)	10 (12)	22	Yes (weak)
Spoerer Minimum	11	22	Yes
normal period (1540-1640AD)	10-11	22	No
Maunder Minimum	13-15	24-29	Yes

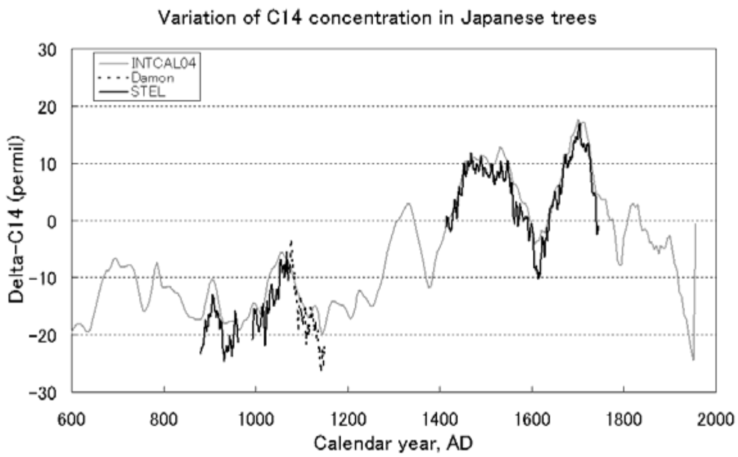

Figure 1: Compilation of our radiocarbon content (black solid curve) with INTCAL04 data (gray curve) from 600 AD to the present, together with Damon's data (black broken curve) for the 11-12th century.

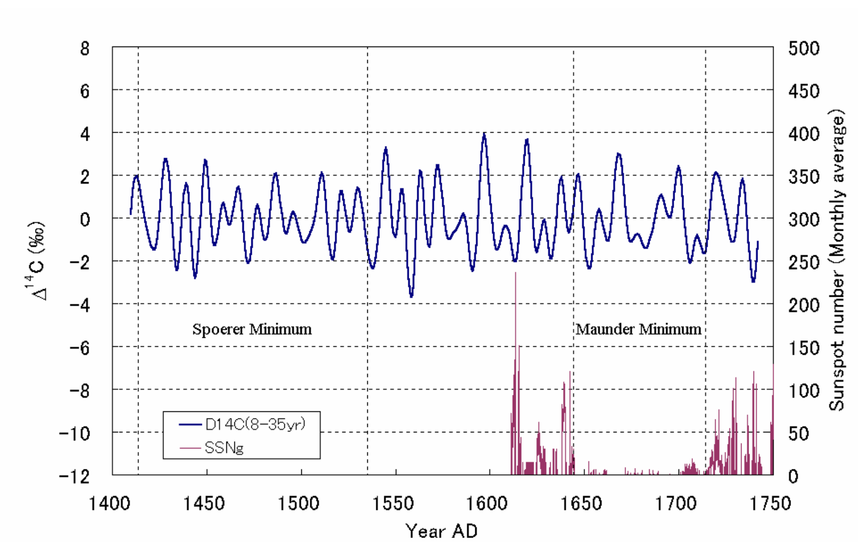

Figure 2: Radiocarbon content from 1413 to 1745 AD filtered with 8-35 years. Monthly sunspot number observed by telescope is also shown. Terms of the Spoerer Minimum and the Maunder minimum are indicated by vertical broken lines.