Variation of Solar "11-year cycle" during the grand solar minimum in the 4th century B.C. by measurement of ^{14}C contents in tree rings

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Abstract: Sunspot numbers, which reflect solar activity, have presented around 11-year periodicity since the early 18th century. However in the period around 1645 to 1715 AD sunspots were almost absent, and this period is called the Maunder Minimum, one of grand solar minima implying weak solar activity. Variation of solar activity in grand solar minima can be investigated by determining the concentration of cosmogenic isotope ^{14}C in annual tree rings. We obtained the ^{14}C records of 1413 to 1745 AD including the Spörer Minimum and the Maunder Minimum with annual time resolution. As a result of frequency analysis of these ^{14}C records, we found that the length of the "11-year cycle" during the Maunder Minimum was around 14 years while that during the Spörer Minimum was around 11 years. This suggests that a pattern of the "11-year" cycle length variation depends on a type of minima classified by their duration of ^{14}C increase. In order to verify this hypothesis, we have measured ^{14}C contents in Japanese camphor tree rings during a possible grand solar minimum in the 4th century B.C.

Introduction

Solar activity alternates between active phase and quiet phase with a period of 11 years. The sun reverses its magnetic polarity when the activity reaches maximum every 11 years, so that after 22 years, the polarity returns to the original state. The sunspot number, which is one of the most obvious indices of solar activity, has presented an 11-year periodicity since the early 18th century when telescopic observation of the sun was started. This 11-year periodicity of solar activity is called the Schwabe cycle, and the 22-year periodicity of magnetic polarity reversal is called the Hale cycle. However sunspots were almost absent between the middle of the 17th century and the early 18th century and did not seem to have noticeable periodicity. This period is called the Maunder Minimum, which is one of grand solar minima implying an extremely weak solar activity. As above, solar activity has long term variation whose timescale is several decades or more than a hundred of years other than the Schwabe cycle. A mechanism of this long term variation has not been understood yet.

We investigate a variation of solar activity in grand solar minima by measuring the concentration of ^{14}C in annual tree rings. ^{14}C is produced in upper atmosphere by galactic cosmic rays (GCR), whose intensity on the earth is affected by solar magnetic field. Therefore, the atmospheric ^{14}C concentration has inverse correlation with solar activity. Atmospheric carbon is absorbed by trees in the form of CO_2 and forms annual rings of trees. Thus we can examine a solar activity in the past by determining the concentration of ^{14}C in tree rings. Decadal ^{14}C records of the last 10,000 years [1] shows the existence of several peaks of ^{14}C concentration with the duration of tens to a hundred years, suggesting grand solar minima (fig.1). We concentrate our investigation to the property of the Schwabe cycle in grand solar minima by determining annual ^{14}C records, and would like to shed some light on understanding of the long-term variation of solar activity.

We obtained the ^{14}C records of 1413 to 1745 AD including the Spörer Minimum and the Maunder Minimum with annual time resolution. As a result of frequency analysis of these ^{14}C records,

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we found that the cycle length of the Schwabe cycle during the Maunder Minimum was around 14 years while that during the Spörer Minimum was around 11 years [2]. The cycle length between the end of the Spörer Minimum and the beginning of the Maunder Minimum was also around 11 years [4]. Stuiver classified grand solar minima into two types, the Maunder type minima which persists around 80 years and the Spörer type minima which persists around 120 years [3]. Our results suggest that a cycle length variation of the Schwabe cycle might be dependent on the type of minima.
In order to examine this hypothesis, we started measurements of ^{14}C contents in Japanese camphor tree rings from a possible grand solar minimum in the 4th century B.C., which is considered to be one of the Maunder type minima. This ^{14}C peak starts at the end of the 5th century B.C.and lasts about 150 years. In this paper, we present a preliminary result on the dating of sample tree.

Method

The sample was a Japanese camphor tree (fig.2) excavated from the bottom of Fukushima River, Miyazaki in southern Japan (31° 28′ N and 131° 14′ E). The number of the tree rings of this sample is about 300.
We extracted carbon from each tree ring, and measured contents of carbon isotopes using an accelerator mass spectrometer (AMS) at Nagoya University.
To estimate the sample age, we compared our measured data set with those of INTCAL04 [1] using chi-square test. The chi-square is defined as;

$$\chi^2(t) = \frac{1}{N}\sum_{n=1}^{N}\left(\frac{A_{int}(t-1+y_n) - A_{ste}(n)}{\sqrt{\sigma^2_{int}(t-1+y_n)+\sigma^2_{ste}(n)}}\right)^2,$$

where t is the assumed age of the innermost ring, n is our sample number counted from the innermost ring, N is the number of data, $A_{ste}(n)$ is the ^{14}C age measured for the nth sample, $A_{int}(y)$ is the ^{14}C age by INTCAL04 for the calendar year y and was calculated by linear interpolation of existing INTCAL04 data [1], y_n is the year of the nth sample, σ_{int} and σ_{ste} are the standard errors of A_{int} and A_{ste}, respectively.

Resuslts

To obtain a rough estimate of sample age, we measured the ^{14}C contents in 4 rings. Using chi-square test, the age of the innermost tree-ring was estimated to be 451(+16,-51) B.C. that is around the begining of the peak of ^{14}C increase. The error of the age was obtained as a region for $\chi^2(t) - \chi^2_{min}(t) \leq 1$.
Then we measured ^{14}C contents of about 60 rings covering about 120 years biennially. Measurement was done from the innermost (the oldest) ring to outer (newer). More accurate dating of the tree was obtained by chi-square test using these data. Thus estimated age of the innermost tree-ring was 431($\pm$12) B.C. as shown in fig.3. This result confirm that our data set covers the period from the beginning of the ^{14}C increase to its top. On the whole, our results agrees with the INTCAL04 data. However, in more detail, ^{14}C contents may fluctuate from INTCAL04 possibly due to the solar cycle. We will carry out more measurements to examine the property of the Schwabe cycle.

Conclusion

We have measured the ^{14}C contents of about 60 rings of a Japanese camphor-tree. As a result of dating, using chi-square test, our data set covers around the beginning of the ^{14}C increase to its top. We will carry out more measurements to clarify the property of the Schwabe cycle in the peak of the 4th century B.C., and compare it with that in the Maunder Minimum.

References

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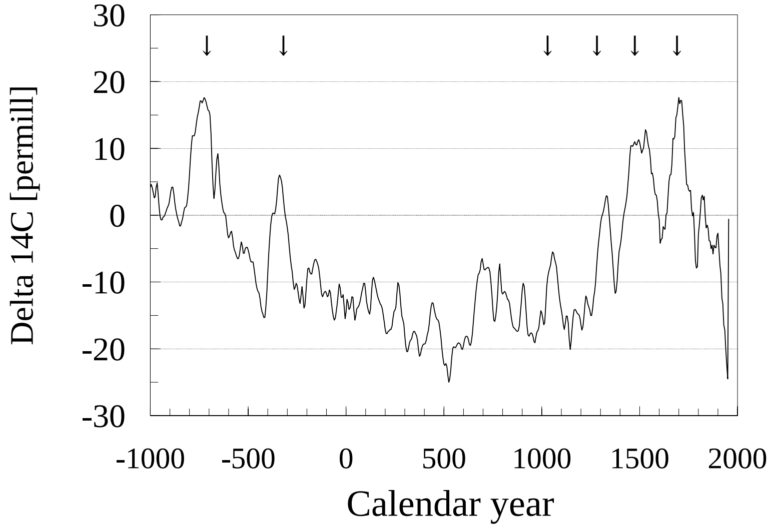

Figure 1: The INTCAL04 data set [1] of the last 3000 years. The ordinate is the concentrations of ^{14}C, and the abscissa is the calendar year. The arrows mean the ^{14}C concentration peaks suggesting the grand solar minimum.

Figure 2: A picture of the smple tree disc.

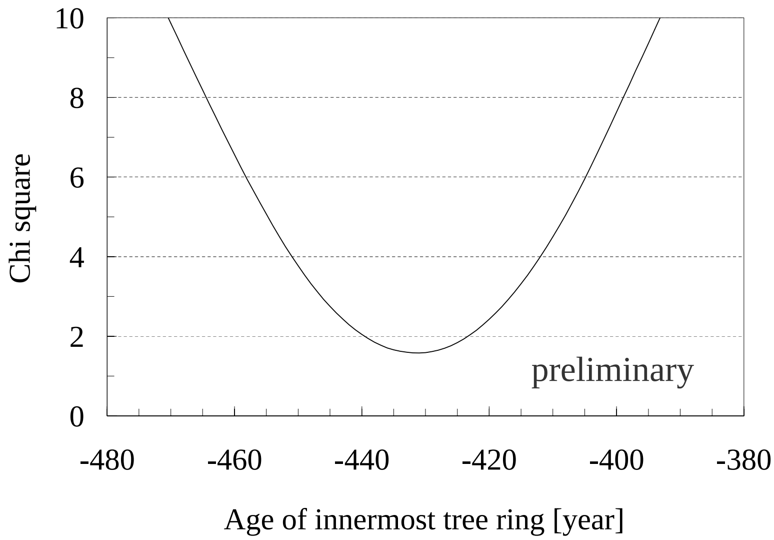

Figure 3: Variation of chi-square value for the age of the innermost tree ring. Negative year means B.C.