Variation of the solar cycle length during the grand solar minimum in the 4th century B.C. deduced from carbon-14 contents in annual tree rings

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***Abstract*. Variation of the sunspot number, which reflects solar activity, has shown the periodicity of around 11 years since the early 18th century. The periodicity is called the Schwabe cycle. However, in the period of 1645 to 1715 AD sunspots were almost absent, and this period is called the Maunder Minimum, one of grand solar minima implying extremely weak solar activity. Carbon-14 (^{14}C) is one of cosmogenic nuclides. Atmospheric ^{14}C concentration shows inverse correlation with solar activity. So ^{14}C content in tree rings which have been constructed from atmospheric carbon dioxide provides important information on past changes of solar activity. The decadal ^{14}C record in recent 10,000 years shows about 20 events of increase in ^{14}C content, indicating grand solar minima. These possible grand solar minima are classified into 2 or 3 groups by the difference of their duration. Spoere-type minima have a duration of about 120 years, and Maunder-type minima have that of about 80 years. We determine the ^{14}C contents in annual tree rings to investigate the common characteristic feature of the Schwabe cycle in the periods of grand solar minima. Preliminary result shows the Schwabe cycle length during the minimum in the 4th century B.C. was several years longer than 11 years, as in the Maunder Minimum.**

***Keywords*: solar cycle, carbon-14, grand solar minima**

I. INTRODUCTION

Solar activity alternates between active phase and quiet phase with a period of 11 years. 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. This 11-year periodicity of solar activity is called the Schwabe 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 is clearly shown in Fig.1 [1]. This period is called the Maunder Minimum, which is one of grand solar minima implying an extremely weak solar activity. Thus, solar activity has long-term variation whose timescale is several decades or more than a hundred of years other than the Schwabe cycle. Additionally, the period of the Maunder Minimum coincides with the period of the Little Ice Age (LIA), when the global temperature cooled down slightly. It is suggested that there are some association between the solar activity and the earth's climate. So when we estimate the solar effect on the earth's climate, it is important to know how the sun act over long periods of time.
Radiocarbon ^{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 carbon dioxide and constructs annual rings. Although the atmospheric ^{14}C concentration is affected by not only solar activity but also earth's magnetic field and carbon cycle system, we assume that the several years to over centurial variation is dominantly affected by the solar activity . We investigate the characteristic variation of the Schwabe cycle in grand solar minima by measuring the concentration of ^{14}C in annual tree rings.

II. PURPOSE

Decadal ^{14}C record of the last 3,000 years (Fig.3)[2] shows the existence of several peaks of ^{14}C concentration with the duration of tens to a hundred years. These peaks suggest the grand solar minima. Miyahara et al. obtained the ^{14}C records of 1413-1745 A.D. including the Spörer Minimum (1416-1534 A.D.) and the Maunder Minimum with annual time resolution. As a result of frequency analysis of these ^{14}C records, they found that the length of the Schwabe cycle during the Maunder Minimum was around 14 years [3] while that during the Spörer Minimum was modulated from 11-years slightly [4]. But as for the Spörer Minimum, recent study shows arround 13-years periodicity in 1395-1435 A.D. which is a pre-minimum term of the Spörer Minimum [5]. The cycle length between the end of the Spörer Minimum

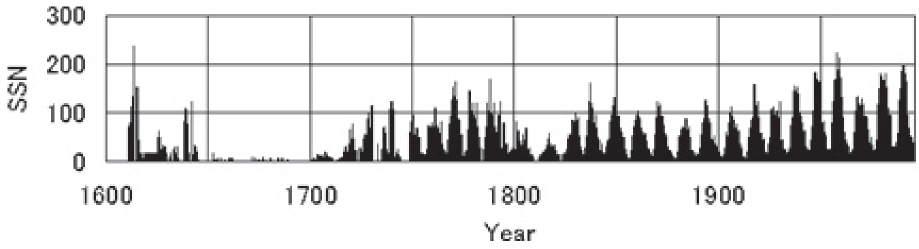

Fig. 1: Observed sun spot number (SSN) from 1610 to 1995 A.D. [1].

and the beginning of the Maunder Minimum was around 11 years [6]. Stuiver classified grand solar minima into two types. Estimated (or real) sunspot absence in the Maunder-type minima persists around 80 years and that in the Spörer-type minima persists around 120 years [7]. What we would like to elucidate is mentioned below. First, is there a certain association between grand solar minima and the variation of the Schwabe cycle length ? Second, when the change of the Schwabe cycle length appears in the duration of the ^{14}C peak ? Final, are there any differences of the pattern of the cycle length change between Maunder-type minima and Spörer-type minima ? In order to examine these issues, 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 (estimated sunspot absence lasted about 80 years). In this paper, we present a preliminary result of the ^{14}C measurement and frequency analysis for our data.

III. METHOD

The sample is a Japanese camphor tree (fig.2) excavated from the bottom of Fukushima River, Miyazaki in southern Japan (31° 28′ N and 131° 14′ E). We chemically extracted graphite through cellulose from each tree ring, and measured contents of carbon isotopes using the accelerator mass spectrometers (AMS). General procedure is mentioned in TABLE I.

TABLE I: Sample States and Treatment

Sample state	Treatment
Tree Rings	Chemical Washing
↓	
Cellulose	Combustion and Purification
↓	
Carbon Dioxide	Reduction
↓	
Graphite	AMS Measurement

We measure the global standard sample (NIST new oxalic acid SRM4990C) and tree ring sample and calculate Δ^{14}C [8]. Typically the measurement error due to AMS is considered to be dominated by the statistical error of ^{14}C counts. It is typically 3-4 per mil. Meanwhile, the amplitude of the Δ^{14}C caused by the Schwabe cycle is about 2-3 per mil. The value, 2-3 per mil is an value of the actual Δ^{14}C data of the period between 1750 and 1954 measured by Stuiver [9]. Because the signal/noise ratio is about 0.5-1, it is not easy to detect the change of the Schwabe cycle length. In this study we divided the tree ring samples at the cellulose stage and measured the contents of carbon isotopes using 2 different AMS systems (at Nagoya University and MALT; Micro Analysis Laboratory, Tandem Accelerator The Universtiy of Tokyo) for the purpose of obtaining high-precision data and the assessment of the repeatability. We obtained two data sets covering the 4^{th} century B.C. grand solar minimum biyearly. To determine the sample absolute age, we compared our data sets with those of IntCal04 [2] using chi-square test [10].

Fig. 2: The picture of the sample camphor tree.

IV. RESULT

Fig.4 shows 3-year running averages of our 2 data sets and IntCal04. Both of our data sets deviate from IntCal04 possibly due to the solar cycle. However it is hardly to say that both data sets agrees with each other in the statistical errors (χ^2=96.8, dof=54, P$\sim 10^{-4}$). We should take the errors from the measurement systems into account as the total measurement errors. But in this papper, we have not considered it yet, and we treat the

2 data sets as the preliminary results. As a result of frequency analysis applying the S-transform, which is one of wavelet-analysis [11], to both data sets independently, both data sets show the same periodicity of arround 15 years at the period 370-340 B.C. This period corresponds to the time when Δ^{14}C value approach the maximum in the 4^{th} century B.C. This behavior is similar to that in the Maunder Minimum. It may suggest that the Schwabe cycle length in the Maunder type minima get several years longer than 11 years toward the top of the Δ^{14}C peak.
We will take the errors from the measurement systems into account as the total measurement errors and combine our 2 data sets of 4^{th} century B.C.

V. Conclusion and Future prospects

We measured ^{14}C contents in single tree rings of Japanese camphor tree (434-284 B.C. biyearly) for the purpose of detecting the some common characteristic behaviors of the Schwabe cycle in the M-type grand solar minima. Preliminary results show the length of the Schwabe cycle got several years longer than 11 years in the time toward the top of the ^{14}C peak. It may be the common behavior with the Maunder Minimum.
We will measure the ^{14}C contents in Japanese cedar tree rings from a possible grand solar minimum in the 7^{th} century B.C., which is considered to be one of the Spörer-type minima to compare with the behavior of the Schwabe cycle in the Spörer minimum. Furthermore, we will compare Maunder-type minima and Spörer-type minima to investigate whether are there any differences of the pattern of the cycle length change. Characteristic behaviors revealed by our research will constrain the solar dynamo models numericaly for the grand solar minima. It would also contribute to construct the several decades to centurial prediction model of the earth's climate.

References

[1] Hoyt, D. V. and Schatten, K. H., Solar Phys., 181, 491-512, 1998
[2] Reimer, P. J., et al., Radiocarbon, 46, 1029-1058, 2004
[3] Miyahara, H., et al., Solar Physics, 224, 317-322, 2004
[4] Miyahara, H., et al., J. Geophys. Res., 111, A03103, 2006
[5] Miyahara, H., et al., In preparation
[6] Miyahara, H., et al., Adv. Space Res., 40, 1060-1063, 2007
[7] Stuiver, M. and Braziunas, T. F., Nature, 338, 405-408, 1989
[8] Stuiver, M., Radiocarbon, 25, 793-795, 1983
[9] Stuiver, M., et al., Radiocarbon, 40, 1041-1083, 1998
[10] Nagaya, K., et al., Proc. 30th ICRC
[11] Stockwell, R., G., Mansinha, L., and Lowe, R., P., IEEE Trans Sig. Proc., 44, 1996

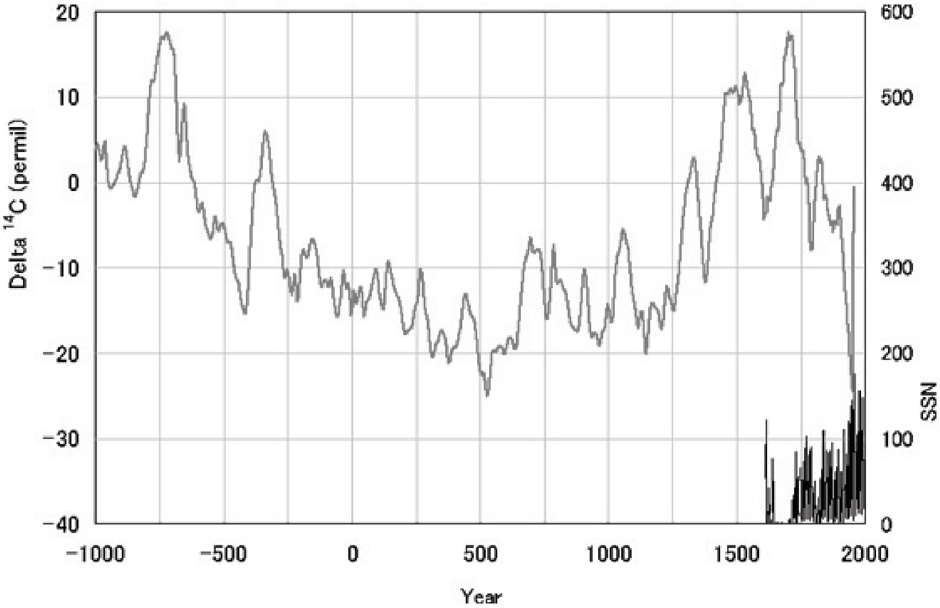

Fig. 3: IntCal04 ^{14}C data of last 3000 years (gray line) [2], and SSN same as Fig.1 (black line).

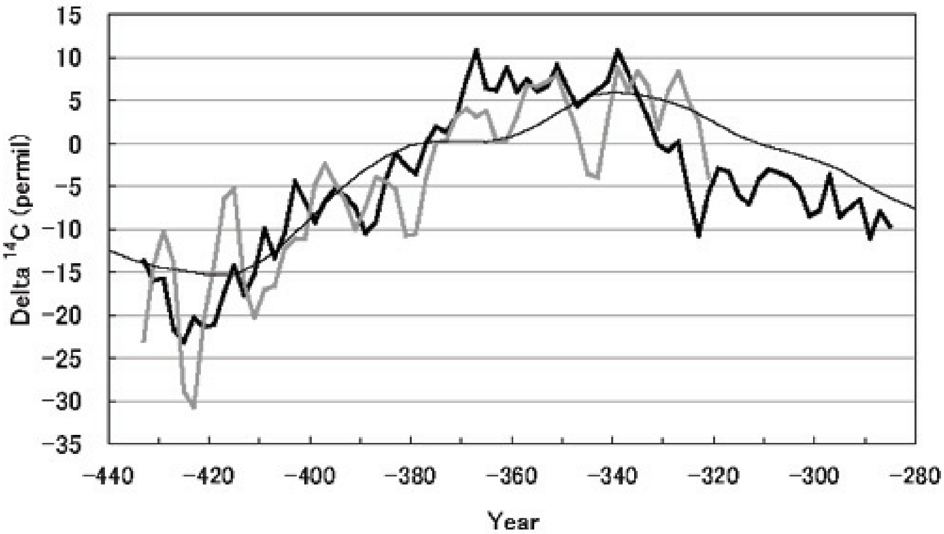

Fig. 4: The result of our measument and IntCal04. Thin black line is IntCal04, thick black line is 3-year running averages of our data measured at Nagoya University and gray shick line is the same but measured at MALT.