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Rapid events in the carbon-14 content of tree-ring

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Abstract: Measurement of cosmogenic nuclides can provide us important information to search past extraterrestrial high-energy events such as supernova, solar proton event (SPE), and so on. Until now, the contents of ^{14}C in tree rings and ^{10}Be in ice cores have been used for this purpose. However, no clear evidence has been found by ^{14}C and ^{10}Be. We show the results of ^{14}C content measurement in Japanese cedar annual rings from AD 600 to 1020 with 1- to 2-year resolution, and report two findings of rapid increases of ^{14}C content from AD 774 to 775 and from AD 992 to 993. These are clear increases against its measurement errors. The shapes of the two series are very similar, i.e., a rapid increase within one year followed by a decay due to the carbon cycle. The scale of the AD 993 event is 0.6 times as large as the AD 775 event. The ^{10}Be flux in the Antarctic ice core also shows peaks corresponding to these two ^{14}C events. The proportions of flux increase ($^{14}C/^{10}Be$) of the two events are consistent with each other. Therefore, it is highly possible that these events have the same origin. Although the cause of the AD 775 event can be explained by a large solar proton event (SPE) or a short gamma-ray burst, we conclude that solar activity is a plausible cause because the occurrence rate of ^{14}C increase events is inconsistent with an observed rate of short gamma-ray bursts.

Keywords: cosmogenic nuclide, radiocarbon, tree-rings, cosmic ray event

1 Introduction

Radiocarbon ^{14}C is produced in the Earth's atmosphere by nuclear interactions of galactic cosmic rays. Radiocarbon oxidizes in the atmosphere to form $^{14}CO_2$ and is taken by trees as a part of the global carbon cycle. As ^{14}C is a radioisotope with a half-life of 5,730 years, the ^{14}C content in tree rings provides a record of cosmic ray intensity over a few tens of millennia.

If a cosmic high-energy phenomenon such as gamma-ray events or large solar proton events (SPEs), which increased incoming cosmic ray intensity rapidly, had occurred in the past, it is possible that tree rings would record such an event. Although there are some periods when ^{14}C content is measured yearly (that are AD 1374 to 1954 [1-4], BC431-281 [5]), they do not show a rapid increase. However, due to some periods in time having missing data, it is possible that such rapid events are hidden in these periods.

In order to search for these cosmic-ray events, we looked at IntCal decadal data which is a ^{14}C dataset back to about 25,000 years BP and is mainly from north American and European trees [6]. If such events had occurred in the past, it is possible that decadal IntCal data would show a rapid increase. For the last 3000 years, only three periods in this time series show a rate of increase (change in the amount of ^{14}C content/time) larger than 3 ‰/10 years, at approximately BC 675 to 655, AD 760 to 785, and AD 1790 to 1820 (figure 1). However, only the 8th century event was not measured with a 1-year resolution. Then, we decided to investigate this period (including AD 760 to 785).

Here, we report the measurement of ^{14}C content from AD 550 to 1100 with 1- to 2-year resolution, and the finding of two rapid ^{14}C increases. They are the AD 775 event and the AD 993 event which are described mainly in Miyake et al. 2012 and 2013 [7,8], respectively.

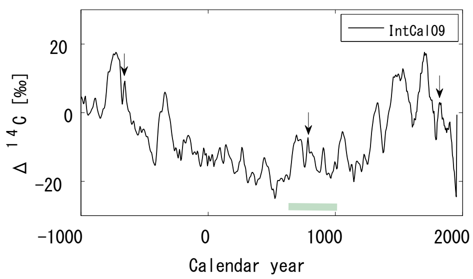

Fig. 1: IntCal09 dataset of ^{14}C content covering the past 3000 years, each points representing a five-year interval [6]. $\Delta^{14}C$ means permil (‰) deviation of $^{14}C/^{12}C$ ratio of a sample with respect to the modern carbon, after correcting for the age and isotopic fractionation [8]. The variation of the ^{14}C content is caused by the change of the cosmic ray intensity, which is mainly modulated by the solar magnetic activity and geomagnetic field. The arrows indicate periods when the rate of increase was larger than 3 ‰ / 10 years. Green line indicates our measurement period.

2 Method

We used two individual Japanese cedar trees (*Cryptomeria japonica*, tree-A and tree-B). To measure ^{14}C content in tree rings, we have to extract graphite from the wood samples. First, we separated each annual ring using a cutter knife. Then, we obtained cellulose, which does not move between rings after the rings are formed, by applying a chemical wash for each wood slice. The chemical wash consists of ultrasonic cleaning, acid-alkali-acid treatments, sodium chlorite treatment and neutralization process. The treated material was combusted to CO_2 and purified in vacuum lines. Finally, purified CO_2 is graphitized by hydrogen reduction under the catalytic influence of iron powder.

We measured the ^{14}C content in extracted graphite using an accelerator mass spectrometer (AMS) at the Center for Chronological Research [9]. As AMS provides a relative measurement, six standard samples (NIST SRM4990C oxalic acid, the new NBS standard) were measured in the same batch. Two blank samples were also measured to determine the background (commercial oxalic acid was obtained from Wako Pure Chemical Industries). The concentration of ^{14}C expressed as Δ^{14}C, which is the age- and isotopic fractionation-corrected value, was calculated according to the method by Stuiver and Polach [10].

3 Results

3.1 The AD 775 event

Although IntCal decadal data shows the ^{14}C content increase about 7.2 ‰ over 10 years (775-785 AD), we observe an increase of 12 ‰ within 1 year (AD 774-775) from our ^{14}C content measurements of two trees [7]. The significance of this increase (AD 774-775) with respect to the measurement errors is 7.2σ. After the ^{14}C content was increased, it shows a decrease over several years. This decay is explained by the carbon cycle [7,11]. The shape of this ^{14}C variation (a rapid increase followed by a decay) is very similar to that of the bomb effect, which was caused by many tests of nuclear explosion in the atmosphere (after the 1950s). The variation of the bomb effect is the best example of a short-term ^{14}C input into the atmosphere. Therefore, the AD 775 event is consistent with a short-term, high energy event producing ^{14}C, followed by a gradual decrease of ^{14}C content due to the global carbon cycle.

In order to compare our results with IntCal98 [12], we averaged the yearly data to obtain a series with decadal time resolution. The two series are consistent with each other within measurement errors. The event causing the increased ^{14}C content in AD 775 could not have been local, because the IntCal data were obtained from North American and European trees, whereas we used Japanese trees.

3.2 The AD 993 event

Since we detected the AD 775 event, we need to know whether more events similar to the AD 775 event exist in the past ^{14}C record. Although the ^{14}C increment around AD 775 is the largest class in the last three millennia from IntCal09 data, there are a large number of period when the ^{14}C content has not been measured with 1-year resolution. Therefore, it is possible that smaller increases than the AD 775 event are hidden in these unmeasured periods.

We measured the ^{14}C content in tree-A during an extended period from AD 822 to 1020 to search other ^{14}C increase events, and found another rapid increase from AD 992 to 993 [8]. The increment is 9.1 ‰ which corresponds to 5.1σ against the measurement errors. A comparison of the AD 775 and the AD 993 events is shown in Figure 3. The shapes of the two series are very similar, that is, a rapid increase within 1 year followed by a decay owing to the carbon cycle. The scale of the AD 993 event is 0.6 times as large as the AD 775 event.

Although the quasi-decadal IntCal09 data set shows a small ^{14}C enhancement around AD 993 (3 permil increase from AD 980 to 995), this increase is hardly distinguishable from many other variations. Therefore, this implies that small increases like the AD 993 event will not be detected until after 1-year resolution measurements.

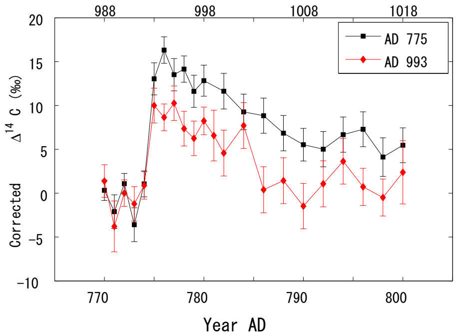

Fig. 2: Squares show the AD 775 series from AD 770-800, and diamonds show the AD 993 series from AD 988-1018. The zero level of the vertical axes is shifted to be the weighted mean value of AD 770-774 for the AD 775 series and AD 988-992 for the AD 993 series.

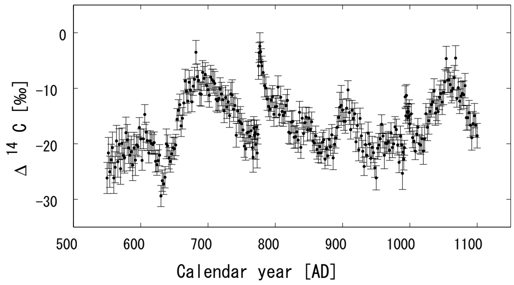

Fig. 3: The consolidated Δ^{14}C data of some series for the period of AD 550 to AD 1100.

3.3 Results from AD 550 to AD 1100

We collected continuous ^{14}C content data from AD 550 to AD 1100. In this period, the ^{14}C data for AD 600 to AD 1020 have been already measured (for AD 600-750: Miyake et al. manuscript in preparation, AD 750-820: Miyake et al. 2012 [7], and AD 822-1020: Miyake et al. 2013 [8]). Therefore, the period of new data is from AD 550-600 and AD 1020-1100. Figure 3 shows the consolidated Δ^{14}C data of some series for the period of AD 550 to AD 1100. Although there are only two significance increases against the errors (the AD 775 and AD 993 events) in this period, there are some smaller gaps (not only increases but also decreases). They are not enough significance against the errors, however, it is possible that they are smaller ^{14}C events. Therefore, we are going to decrease the measurement errors during these small events by multiple ^{14}C measurements, and detect more such events.

4 Discussions

4.1 Cause of ^{14}C events

The ^{14}C content measurements for the recorded ages of supernova explosions (SN1006, SN1054, SN1572, SN1604 and SN1885) and the emergence years of large solar flare (the Carrington flare which occurred in AD 1859) have been conducted. We also measured the ^{14}C content around

SN1054 and SPE1859 using another Japanese cedar tree [8]. However, none of the ^{14}C contents show rapid increases within 1 year. There is no significance ^{14}C increase within 1 year during other periods, from AD 1374 to AD 1954. Therefore, two ^{14}C events must be something bigger than these historical recorded events. At least, the total energy of two ^{14}C events must be 5-8 times larger than these historical events, if an increase of ^{14}C content at historical events were in the same order as the measurement errors (about 2 ‰).

After our paper about the AD 775 event was published, some discussed about the cause of these ^{14}C events, and two candidates for the cause are considered, large solar proton events (SPEs) and short gamma-ray bursts (GRBs).

4.2 Short GRB

For gamma-ray events, there are supernova explosions and GRBs. The supernova remnants corresponding to AD 775 and AD 993 have not been detected and historical documentation has not been found. Therefore, a supernova origin is quite unlikely [7, 13]. Although only the normal supernova origin was considered in Miyake et al. [7], Hambaryan and Neuhauser claimed that short GRBs could cause the AD 775 event [13]. In case of a short GRB, its spectral hardness is consistent with the differential production rates of ^{14}C and ^{10}Be, and explains the absence of historical records of a supernova or a supernova remnant [13].

However, the biggest problem of the hypothesis of short GRB is that the observed rate of short GRB is very low. Although they claim that the observed rate of short GRBs (one event in 3.75×10^{6} years) and that of ^{14}C events (one ^{14}C event in 3,000 years) are consistent within 2.6σ [13]. However, from our second finding of the AD 993 event, the ^{14}C event rate increases, and the consistency between the observed rate of short GRBs and the ^{14}C event rate becomes worse. The probability of a short GRB rate with one ^{14}C event in 1,500 years is 0.04

4.3 Large SPE

Next, we consider the SPE origin. Melott and Thomas have reexamined the flare energy of the AD 775 event by assuming a directional flare with opening angle of 24°, and concluded that implied energy of SPE is reduced to 10^{33} erg [14,15]. This is about 1/100 energy of our calculation [7], which presumes that flare particles propagated isotropically. Then SPE appears to be the possible cause of the AD 775 event.

An emergence of SPE is considered to be closely bound to solar activity, such as solar flares and CMEs. In order to know the solar activity during 8-10th centuries, we have examined the IntCal data set [6]. The variation of ^{14}C content (which is closely related to the flux of galactic cosmic rays reaching the earth) is mainly modulated by the solar magnetic activity and the geomagnetic field. The ^{14}C variation in the past several hundred years reflects the solar magnetic activity as indicated by the sunspot records. In particular, periods of solar inactivity known as grand solar minima can be identified as large peaks in the past ^{14}C content record. The period from the late 13th century to the early 19th century is known as 'little ice age'. On the other hand, the 8-10th centuries have no grand solar minimum. There have been some attempts to reconstruct the solar activity by using ^{14}C data set, and they showed higher solar activity levels during the 8-10th centuries than

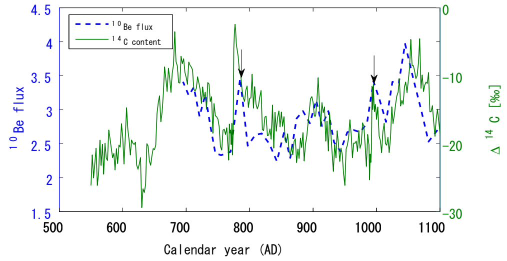

Fig. 4: Comparison with ^{10}Be data from ice core of Dome Fuji in Antarctica and our ^{14}C results. The left vertical axis represents the ^{10}Be flux, which is calculated from the snow accumuration rate, estimated by the three-point (1.5 m: 30 years) averaged δ^{18}O [17]. The unit of left axis is 10^{5} atoms per cm^{2} per year. The right vertical axis represents ^{14}C content. The horizontal axis represents the calendar year. Each point is corrected by a ^{10}Be-^{14}C correlation age model. The two arrows show the ages of around AD 785 and AD 995.

that during the 13-19th centuries, on average [16]. This fact may explain why the 8-10th centuries have two rapid increases of ^{14}C content and after the 11th century there were no such events.

Based on a reassessment of an energy spectrum of SPE, production calculations of ^{14}C and ^{10}Be, and a deposition model, Usoskin and Kovaltsov claimed that the AD 775 event can be explained by an extreme SPE that was about 50 times larger than the largest SPE in AD 1956 [11,17]. From this aspect, the AD 993 event is about 30 times larger than SPE 1956. The energetic level does not have a serious effect on living matter on the earth [14,15]. Also, according to Usoskin and Kovaltsov [17], the occurrence rate of the SPE775 event is 10^{4} per year and that of the SPE993 event is 10^{3} per years. It is possible that these events occur within 200 years assuming that SPEs are mutually independent. Although they claimed that there is no apparent relationship between the occurrence of SPE and the solar activity level, or it is proposed that large SPEs are occurred more likely during grand solar minima, we doubt these claims because the two events occurred in the non-solar minimum period.

4.4 ^{10}Be data

Another cosmogenic nuclide, ^{10}Be, in the Antarctic Dome Fuji ice core also shows increases in the flux corresponding to around AD 775 and AD 993 [17]. Figure 4 shows ^{10}Be flux data for AD 700-1100. The ages of the ^{10}Be data are determined by matching the production rate pattern of ^{10}Be with the ^{14}C production [17]. The increasing rates are 7.2×10^{3} (atoms per cm^{2} per year/year) from AD 770 to 785, and 6.2×10^{3} (atoms per cm^{2} per year/year] from AD 985 to 995. The scale of the increase around AD 993 is 0.86 times as large as that around AD 775. This value is consistent with the ratio for ^{14}C events (0.6 times larger) because ^{10}Be data have a lower time resolution (10 years resolution) than that of ^{14}C data. If the causes of two events are different, a large difference between the ratios of ^{14}C and ^{10}Be production rates is expected. This difference is occurred by energy spectrums or particle species of the origin events. From the consistency of increasing ratio of AD 775 and 993 between ^{14}C and ^{10}Be, the cause of the two events must be same.

Here, we should mention about the ^{10}Be data in the

Greenland ice core. Although the Dome Fuji data show two peaks corresponds to the AD 775 and the AD 993 events, the Greenland data do not show any significant increases. We can explain this difference by a low resolution of the data [17]. However it is better to investigate about this because if there really is a difference between the two hemispheres, the cause of these ^{14}C event are more likely to be the gamma-ray events. Sometimes, the deposition of the ice core is affected by the climatic noise and there is a possibility that ice core has a missing layer. Therefore, we should measure the ^{10}Be concentration with a 1-yr resolution in several cores. Also it will be useful to measure other cosmogenic nuclides such as ^{26}Al and ^{36}Cl in ice cores for further discussion about the cause.

5 Conclusions

We measured the ^{14}C content in tree-rings from AD 550 to AD 1100, and found the rapid increases in AD 775 and AD 993. Considering the ^{14}C event rate and higher solar activity in the 8-10th centuries, a large SPE is a more plausible cause of the ^{14}C increase event. This indicates the possibility that such SPEs will occur in the future. Detection of the second ^{14}C event indicates the possibility that a lot of smaller ^{14}C increases are hidden in the periods when the ^{14}C content has not been measured with a 1-year resolution. In the future, it will be necessary to conduct investigations of ^{14}C records during additional unmeasured periods with a 1-year resolution. In parallel with a long-scale ^{14}C yearly measurement, we should investigate other cosmogenic nuclides in some ice cores to specify the cause of these rapid events.

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References

[1] Stuiver, M., Reimer, P. J. & Braziunas, T. F. High-precision radiocarbon age calibration for terrestrial and marine samples., *Radiocarbon* **40**, 1127-1151 (1998).
[2] Miyahara, H., Masuda, K., Muraki, Y., Kitagawa, H. & Nakamura, T., Variation of solar cyclicity during the Spoerer Minimum., *J. Geophys. Res.* **111**, A03103 (2006).
[3] Miyahara, H. *et al.* Is the sun heading for another Maunder minimum? Precursors of the grand solar minima., *J. Cosmol.* **8**, 1970-1982 (2010).
[4] Miyahara, H. *et al.* Cyclicity of solar activity during the Maunder Minimum deduced from radiocarbon content., *Sol. Phys.* **224**, 317-322 (2004).
[5] Nagaya, K. *et al.* Variation of the Schwabe cycle length during the grand solar minimum in the 4th century BC deduced from radiocarbon content in tree rings., *Sol. Phys.* **280**, 223-236 (2012).
[6] Reimer, P. J. *et al.* IntCal09 and marin09 radiocarbon age calibration curves, 0-50,000 years cal BP., *Radiocarbon* **51**, 1111-1150 (2009).
[7] Miyake, F., Nagaya, K., Masuda, K. & Nakamura, T. A signature of cosmic-ray increase in AD 774-775 from tree rings in Japan., *Nature* **486**, 240-242 (2012).
[8] Miyake, F., Masuda, K. & Nakamura, T. Another rapid event in the carbon-14 content of tree rings., *Nat. Commun.*, DOI: 10.1038/ncomms2783 (2013).
[9] Nakamura, T. *et al.* The HVEE Tandetron AMS system at Nagoya University., *Nucl. Instrum. Methods B* **172**, 52-57 (2000).
[10] Stuiver, M., & Polach, H. A. Discussion: Reporting of ^{14}C data., *Radiocarbon* **19**, 355-363 (1977).
[11] Usoskin, I. *et al.* The AD775 cosmic event revisited: the Sun is to blame, *A&A* **552**, L3, DOI: 10.1051/0004-6361/201321080 (2013).
[12] Stuiver, M. *et al.* INTCAL98 radiocarbon age calibration, 24,000-0 cal BP. *Radiocarbon* **40**, 1041-1083 (1998).
[13] Hambaryan, V. V. & Neuhauser, R. A galactic short gamma-ray burst as cause for the ^{14}C peak in AD 774/5. *Mon. Not. R. Astron. Soc.* **430**, 32-36 (2013).
[14] Melott, A. L. & Thomas, B. C. Causes of an AD 774-775 14C increase. *Nature* **491**, E1-E2 (2012).
[15] Thomas, B. C., Melott, A. L., Arkenberg, K. R. & Snyder B.R. . Terrestrial effects due to possible astrophysical sources of an AD 774-775 increase in ^{14}C production. *Geophys. Res. Lett.* **40**, 1-4, DOI: 10.1002/grl.50222 (2013).
[16] Solanki, S. K., Usoskin, I. G., Kromer, B., Schuessler, M. & Beer, J. An unusually active Sun during recent decades compared to the previous 11,000 years. *Nature* **431**, 1084-1087 (2004).
[17] Usoskin, I. G. & Kovaltsov, G. A. Occurrence of extreme solar particle events: assessment from historical proxy data. *Astrophys. J.* **757**, 92, DOI:10.1088/0004-637X/757/1/92 (2012).
[18] Horiuchi, K. *et al.* Ice core record of ^{10}Be over the past millennium from Dome Fuji, Antarctica: a new proxy record of past solar activity and a powerful tool for stratigraphic dating. *Quat. Geochronol.* **3**, 253-261 (2008).