RESEARCH ON SOLAR ACTIVITY USING ACCELERATOR MASS SPECTROMETRY*

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Abstract

Analyses of cosmic-ray-induced nuclides such as carbon-14 and beryllium-10 in natural archives using the Accelerator Mass Spectrometer (AMS) have been powerful tools for tracing the precise history of solar activity and understanding the underlying mechanisms of solar activity variations on various time scales. In this paper, we present our recently obtained high-precision data of carbon-14 in annual tree rings and our attempts to resolve the history of decadal-scale solar cycle variations using the AMS at Yamagata University. We have found that the length of these cycles tends to increase preceding prolonged sunspot disappearances, known as grand solar minima. This suggests that the meridional flow in the solar convection zone plays an essential role in modulating solar activity levels, providing insights into the solar dynamo mechanism. High-precision analyses have also made it possible to detect relatively smaller but frequent large-scale solar proton events, contributing to the advancement of space weather research. Our analyses indicate that large solar proton events occurred three times during the transitional period of solar activity from high activity condition to the quiet grand solar minimum in the 13th century.

INTRODUCTION

Solar activity exhibits long-term variations on time scales of up to a few millennia, occasionally resulting in sunspot disappearances lasting more than a few decades, which lead to cooling of the Earth's climate [1]. Understanding the mechanisms behind such long-term variations and predicting extreme events are crucial topics in solar physics. Annually resolved records of cosmogenic nuclides, such as carbon-14 in tree rings and beryllium-10 in ice cores or sediments, provide essential information on the characteristics of the fundamental solar activity cycles, which have a period of approximately 11 years. These records are foundational for understanding the processes of solar activity variations. While beryllium-10, with a half-life of 1.39 million years, provides a longer record of solar activity, carbon-14 (half-life: 5730 years) in absolutely dated tree rings is more suited for tracing the precise history of 11-year solar cycles. However, because the amplitude of carbon-14 variations is significantly reduced in the carbon cycle, high-precision measurements are required to accurately retrieve the wave patterns of solar cycles. The variation of galactic cosmic rays (GCRs) incident on the Earth over the solar cycle is approximately 20%, whereas the variation of carbon-14 content in tree rings is reduced to 0.2 to 0.3%. This reduced amplitude is comparable to the typical precision of AMS, allowing only an approximate determination of solar cycle lengths over a few cycles (see the examples in Refs [2] and [3]). Therefore, improving the precision of the measurements was necessary to deepen our understanding of the variations in solar cycles in the past.

HIGH-PRECISION ANALYSES OF CARBON-14 IN TREE RINGS

In order to derive detailed information on the characteristics of each 11-year cycle, our team began efforts to improve measurement precision in 2010 using the compact AMS at Yamagata University [4]. We then achieved a precision of 0.05% in 2021. Figure 1 shows the high-precision data obtained for the period leading to the Maunder Minimum, one of the prolonged periods of sunspot absence that began in the mid-1600s. Based on the 11-box model of carbon cycle, we were able to reconstruct the length of each solar cycle, finding that the length of solar cycles started to lengthen three cycles ahead of the onset of sunspot disappearance in around 1645 CE [5] (see Fig. 2). The longest cycle found was 16 years. The length of the solar cycle has been suggested that it is probably related to the speed of meridional flow inside the solar convection zone. In the case the time-scale of turbulent diffusion of the magnetic field is relatively short, the slow-down of the meridional circulation may enhance the magnetic field dissipation during transportation [8]. This result suggests that the change in the meridional circulation plays an important role in regulating the solar activity level.

High-precision analyses of carbon-14 also allow us to detect large-scale solar proton events associated with the eruption of solar flares. Understanding the characteristics of solar flares to improve prediction ability has been an important subject within the space weather community. Since the discovery of extreme solar proton events in 774-775 CE based on tree-ring carbon-14 data [9], active research has been conducted to explore past solar flares. While a few events of a similar scale to the 774-775 CE event have been found, the number of relatively smaller but more frequent flares is still limited due to detection difficulties. High-precision analyses of carbon-14 have enabled us to explore such relatively smaller events, such as those found during the period leading to the Wolf Minimum that started around 1285 CE [10] (see Fig. 3). There were jumps in the carbon-14 content in the rings of 1262, 1269, and 1280 CE, corresponding to the scale approximately 13%, 27%, and 19% of the 775 CE event, respectively. Based on the carbon cycle model, it was suggested that these events occurred at the maximum or declining phase of the solar cycles, similarly to the large solar proton events observed in the modern era.

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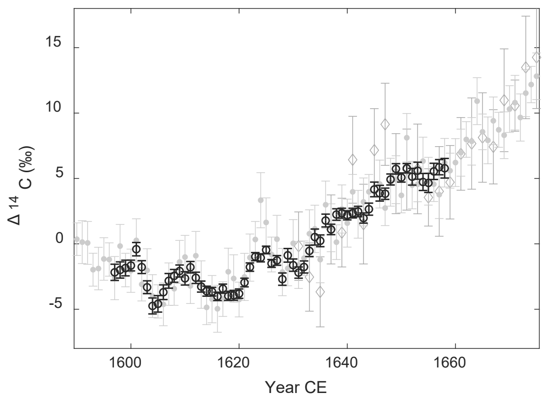

Figure 1: High-precision carbon-14 data obtained for the period leading to the onset of the Maunder Minimum around 1645 CE using the AMS at Yamagata University (black circles) [5], plotted together with the annual data obtained by Brehm et al. (2021) [6] (gray diamonds).

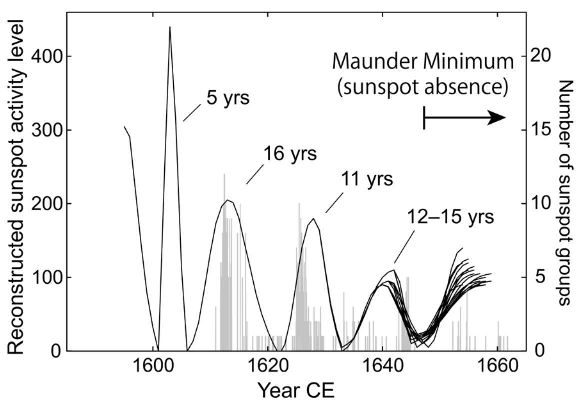

Figure 2: Reconstructed solar cycles based on the high-precision carbon-14 data shown in Fig. 1. Gray lines indicate the sunspot variations observed by telescopes [7].

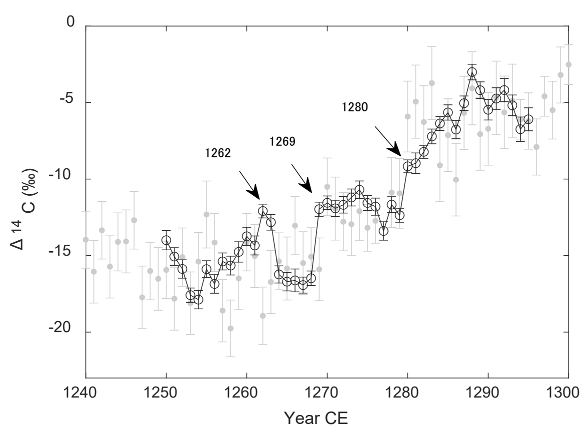

Figure 3: High-precision carbon-14 data obtained for the period leading to the onset of the Wolf Minimum started around 1285 CE.

CONCLUSION

Analyses of carbon-14 using typical AMS precision provided only limited information on past solar activity. However, with high-precision measurements and high temporal resolution, it is now possible to obtain a more detailed history of solar activity, contributing to a better understanding of the solar dynamo and advancements in space weather research. These advancements underscore the importance of continuous improvement in measurement techniques to enhance the understanding of solar and related phenomena.

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REFERENCES

[1] J. Eddy, "The Maunder Minimum," *Science*, vol. 192, no. 4245, pp. 1189-1202, 1976, doi: 10.1126/science.192.4245.1189.

[2] H. Miyahara, K. Masuda, Y. Muraki, H. Furuzawa, H. Menjo, and T. Nakamura, "Cyclicity of solar activity during the Maunder Minimum deduced from radiocarbon content," Solar Physics, vol. 224, pp. 317-322, 2004.

[3] H. Miyahara, Y. Yokoyama, and K. Masuda, "Possible link between multi-decadal climate cycles and periodic reversals of solar magnetic field polarity," Earth and Planetary Science Letters, vol. 272, pp. 290-295, 2008.

[4] M. Takeyama, T. Moriya, H. Saitoh, H. Miyahara, F. Miyake, M. Ohyama, R. Sato, R. Shitara, H. Sakurai, and F. Tokanai, "Present status of the YU-AMS system and its operation over the past 10 years," Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, vol. 538, pp. 30-35, 2023, doi: 10.1016/j.nimb.2023.01.021.

[5] H. Miyahara, F. Tokanai, T. Moriya, M. Takeyama, H. Sakurai, K. Horiuchi, and H. Hotta, "Gradual onset of the Maunder Minimum revealed by high-precision carbon-14 analyses," Scientific Reports, vol. 11, Article 5482, 2021, doi: 10.1038/s41598-021-84830-5.

[6] N. Brehm, A. Bayliss, M. Christl, H.-A. Synal, F. Adolphi, J. Beer, B. Kromer, R. Muscheler, S. K. Solanki, I. Usoskin, N. Bleicher, S. Bollhalder, C. Tyers, and L. Wacker, "Eleven-year solar cycles over the last millennium revealed by radiocarbon in tree rings," Nature Geoscience, vol. 14, pp. 10-15, 2021, doi: https://www.nature.com/articles/s41561-020-00674-0.

[7] J. M. Vaquero, et al., "A revised collection of sunspot group numbers," Solar Physics, vol. 291, pp. 3061-3074, 2016.

[8] A. R. Yeates, D. Nandy, and D. H. Mackay, "Exploring the Physical Basis of Solar Cycle Predictions: Flux Transport Dynamics and Persistence of Memory in Advection- versus Diffusion-dominated Solar Convection Zones," The Astrophysical Journal, vol. 673, pp. 544-566, 2008.

[9] F. Miyake, K. Nagaya, K. Masuda, and T. Nakamura, "A signature of cosmic-ray increase in AD 774-775 from tree rings in Japan," Nature, vol. 486, no. 7402, pp. 240-242, 2012, doi: 10.1038/nature11123.

[10] H. Miyahara, F. Tokanai, T. Moriya, M. Takeyama, H. Sakurai, M. Ohyama, et al., "Recurrent large-scale solar proton events before the onset of the Wolf grand solar minimum," Geophysical Research Letters, vol. 49, 2022, Art. no. e2021GL097201, doi: 10.1029/2021GL097201.