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Variation of the cosmic ray intensity during the Maunder Minimum deduced from carbon-14 content in tree-rings

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In this paper, the variation of cosmic ray intensity during the Maunder Minimum deduced from the variation of carbon-14 content in tree-rings is presented. It has been previously reported that the length of the "eleven-year" cycle was lengthened to be about fourteen years during the Maunder Minimum. We investigate the features of the eleven-year and the twenty-two year variation of the carbon-14 content. The carbon-14 records show remarkable twenty-two year structure which may be due to cyclic magnetic reversal of the Sun. The variation of carbon-14 content suggests that the polarity of the Sun was negative when the Maunder Minimum occurred.

1. Introduction

Cosmogenic nuclides in stratified ice core or tree rings can provide extendable sequences of the indices of solar activity, state of the interplanetary magnetic field and the flux of the Galactic Cosmic Rays (GCRs) to the past when observational records are not available. Cosmogenic nuclides are produced at the earth's atmosphere mainly by the galactic cosmic rays coming from outside of the heliosphere. On the way to the earth, GCRs are modulated by the solar wind and the interplanetary magnetic field. The GCRs interact with the earth's atmosphere and produce showers of secondary cosmic rays that in turn produce cosmogenic nuclides. Generally, intense solar activity results in a decrease of production rate of cosmogenic nuclides while weakening of solar activity brings an increase. Carbon-14, which is one of the cosmogenic nuclides is produced by the neutron capture on nitrogen nuclei and is absorbed into tree-rings by photosynthesis after circulating in the carbon cycle as the form of CO_2.

In the previous paper, we have investigated the features of solar cycle during the Maunder Minimum, which is the period of prolonged sunspot minima from 1645 AD to 1715 AD, by measuring the carbon-14 content in the Japanese cedar tree with annual time resolution [1]. The sunspot activity has shown scarcely the cyclic structure for this period. However, the frequency analysis of the carbon-14 record has shown significantly the period of about 13-15 years together with the period of about 23-29 years, which suggest the persistent cyclic magnetic reversals of the Sun through the Maunder Minimum with the period several years longer than that of recent solar activity.

In this paper, we investigate more detailed features of the "eleven-year" and the "twenty-two year" variation of carbon-14 content and examine the correlation with the sunspot activity. It has been suggested that the flux of GCRs is relatively higher when solar polarity is negative than the period when the polarity is positive during the prolonged solar activity minimum [3]. Based on this idea, we examined the possible transition of solar polarity during the Maunder Minimum.

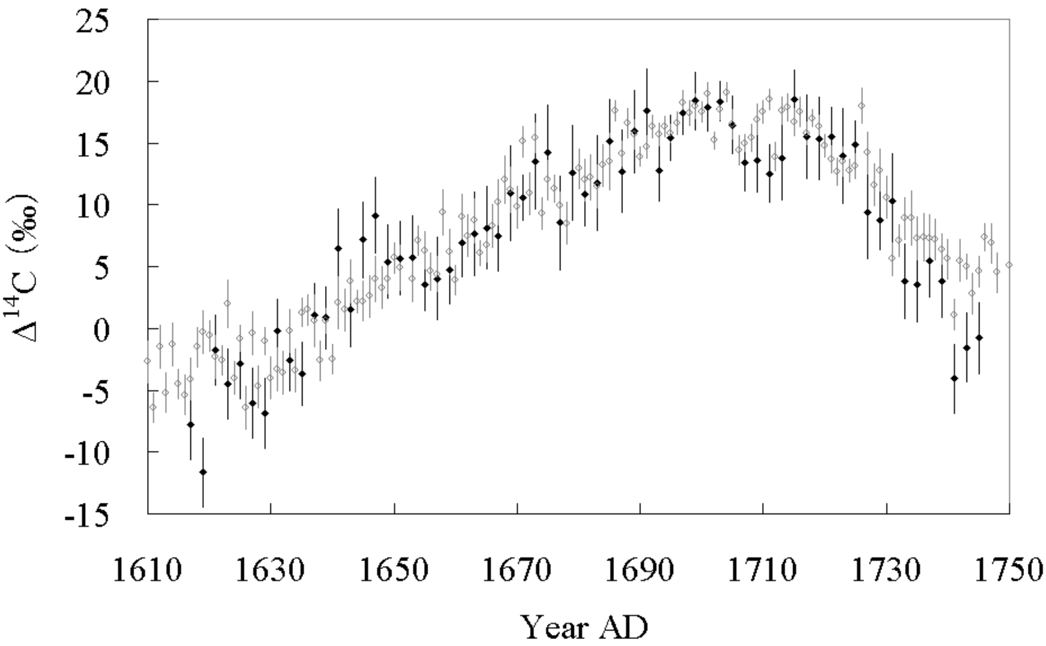

Figure 1. Records of carbon-14 content in tree-rings from 1610 AD to 1750 AD, including the whole Maunder Minimum. Carbon-14 data with bi-annual time resolution obtained by our group (dots) are now available from 1617 AD to 1745 AD. Circles show the annual carbon-14 data obtained by Stuiver et al. (1998).

2. Discussion

We have slightly extended our record of carbon-14, which had been obtained for the period from 1631 AD to 1739 AD [1]. The data are now available from 1617 AD to 1745 AD with bi-annual time resolution. Figure 1 shows the results of our measurement and the annual carbon-14 data obtained by Stuiver et al. [2].

In order to extract the "eleven-year" variation and the "twenty-two year" variation in carbon-14 records in Figure 1, the data were band-pass filtered with the bandwidth of 10-18 years (Figure 2) and 10-35 years (Figure 3). Both of the data have been plotted inversely together with the group sunspot number, and the time lag between the production in the atmosphere and the absorption into trees has been taken into account. We assumed that the time lag is about three years.

It is evident from the carbon-14 records in Figure 2 that the GCRs had retained cyclic variation through the Maunder Minimum with almost constant amplitude, even though such significant variation is not seen in the sunspot record. As is suggested by the spectral analysis of carbon-14 records, the length of the cycle seems to be lengthened only during the Maunder Minimum. Consequentially, it can be concluded that the number of the solar cycle during the seventy years from 1645 AD to 1715 AD was no more than five.

Figure 3 exhibits the features of the "twenty-two-year" variation of carbon-14, which can be caused by the modulation of the GCRs dependent on solar polarity [3]. It can be recognized that the length of the "twenty-two year" cycle is also lengthened in association with the lengthened "eleven-year" cycle. It has been suggested that the flux of the GCRs is relatively higher when solar polarity is negative during the Maunder Minimum. The periods of high concentration, appearing at around 1645 AD, 1670 AD and 1700 AD might be correspond to the period when solar polarity is negative.

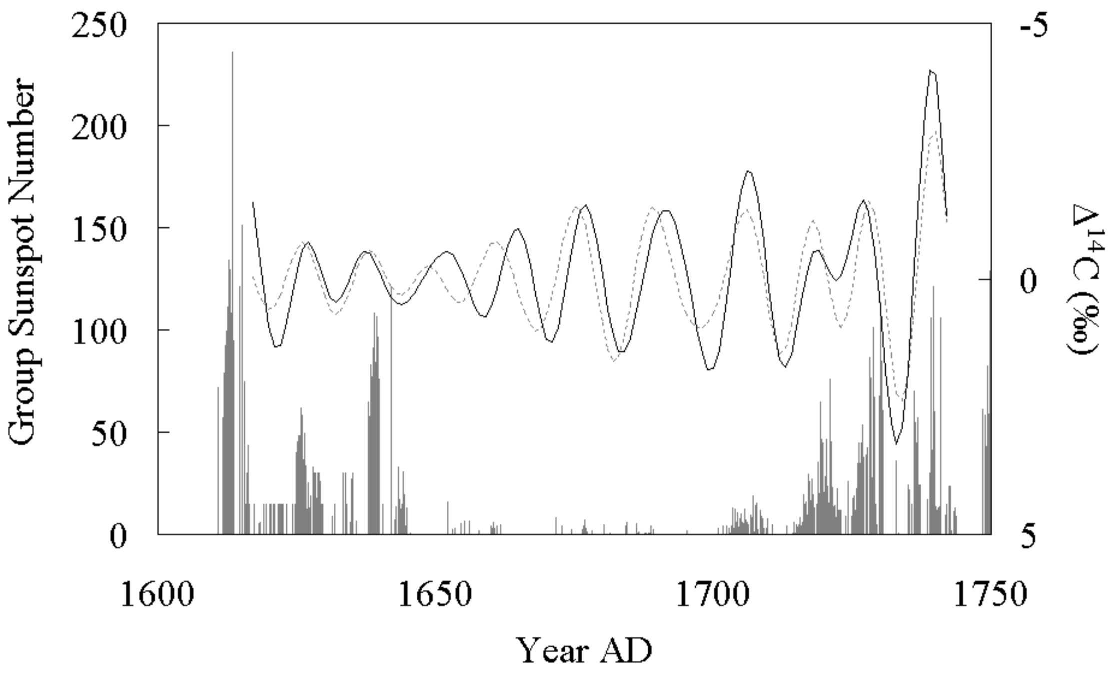

Figure 2. Monthly group sunspot activity and the band-pass filtered carbon-14 records with the bandwidth of 10-18 years. Not that the carbon-14 data are plotted inversely. The time-lag in the carbon cycle has been also taken into account. The solid curve shows the band-pass filtered carbon-14 data obtained by this study (dots in Figure 1), and the dotted curve shows the band-pass filtered carbon-14 data (circles in Figure 1) obtained by Stuiver et al. (1998).

Such an appearance of the twenty-two year cycle is also recognizable in the variation of carbon-14 content during the Spoerer Minimum (1415-1534 AD). The twenty-two year structure is seen as the suppression of every other peak, which might be also suggesting the periods of solar polarity negative.

3. Conclusions

In both of the carbon-14 records for the Maunder and the Spoerer minima, twenty-two year structure is detected. It suggests that the Sun had retained the polarity reversal through the prolonged sunspot minimum period. By analyzing the detailed variation of the twenty-two year cycle, it may be possible to determine the polarity of the Sun in the past when the observational records are no longer available.

4. Acknowledgements

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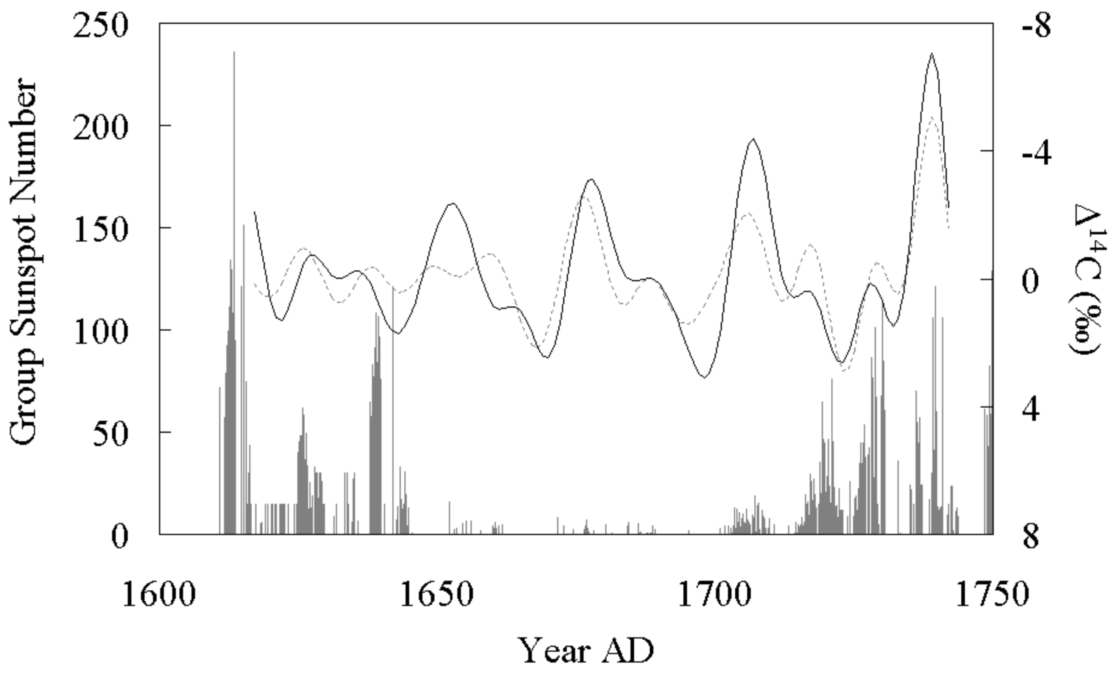

Figure 3. Monthly group sunspot activity and the band-pass filtered carbon-14 records with the bandwidth of 10-35 years. Not that the carbon-14 data are plotted inversely. The time-lag in the carbon cycle has been also taken into account. The solid curve shows the band-pass filtered carbon-14 data obtained by this study (dots in Figure 1), and the dotted curve shows the band-pass filtered carbon-14 data (circles in Figure 1) obtained by Stuiver et al. (1998).

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