PAPERS

The nature of the solar activity during the Maunder Minimum revealed by the Guliya ice core record

Wang Ninglian[1], L. G. Thompson[2] & J. Cole-Dai[2]

1. Laboratory of Ice Core and Cold Regions Environment, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China;
2. Byrd Polar Research Center, Ohio State University, Ohio 43210, USA

Abstract Whether the solar activity was very low, and especially whether the solar cycle existed, during the Maunder Minimum (1645—1715 AD), have been disputed for a long time. In this paper we use the Guliya NO_3^- data, which can reflect the solar activity, to analyze the characteristics of the solar activity during the Maunder Minimum. The results show that the solar activity was indeed low, and solar cycle displayed normal as present, i.e. about 11a, in that period. Moreover, it was found that the solar activity contains a 36-year periodic component probably, which might be related to the variations in the length of the sunspot cycle. This finding is of importance for the study of the relationship between the sun variability and the Earth climate change.

Keywords: **Maunder Minimum, solar activity, Guliya ice core.**

The impact of the sun on climate has been reflected not only by the climatological observation data and statistically analytical results of the records in ice core, tree ring, lacustrine deposits[1—4], etc., but also by the recent numerical modelling results[5, 6]. Especially, that the simulation results of global climate model with consideration of influence of UV radiation on stratospheric chemistry[5] were supported by meteorological observation data[7] improves our knowledge about the mechanism of the impact of solar variability on the climate change[8—10]. At present, the high-resolution climatic and environmental changes during the past 400 ka were reconstructed through ice core records on different time scales[1, 11—17], but systematic observation for the solar activity just began in 18th century. Therefore, it is necessary to investigate the proxies of the solar activity for establishing the long-term changes of the sun and understanding the solar-terrestrial relationships. Besides the sunspots, the aurora, $\Delta^{14}C$ in tree ring, ^{10}Be in ice core, and geomagnetic index aa are good proxies of the solar activity. Most recently, it was found that NO_3^- concentration recorded in the Guliya ice core might also provide information of the solar activity, and there was a positive relationship between them[18], because the major source of NO_3^- in this ice core came from the NO_x in the high atmosphere which is related with the solar activity[19].

Since Eddy named the period of 1645 through 1715 AD, when the sun was very weak, the Maunder Minimum[20], many scientists have been studying this problem[21—26]. The focuses of the argument for this problem are: (i) whether this Minimum existed; and (ii) how about the nature of the solar activity, i.e. whether the sunspot cycle of about 11a existed during that period. For the former topic, many data supported the existence of the Minimum[24], but recent discovery of the sunspot observation data during the 17th century from European documents[16] makes this Minimum questionable again[27]. As to the solar cycle of about 11a, it was discerned from many geological data[28—33] before the Maunder Minimum and confirmed by the historical observation of the sun after the Minimum, and there was little evidence just in time of this Minimum. However, the continuity of this cycle plays an important scientific role on the solar dynamo theory. It is difficult to figure out the periodicity of 11a from the records of aurora and sunspots in early historical documents and the variations in $\Delta^{14}C$ in tree ring. Because the historical documents only recorded one part of the natural phenomena[34], and there is about 10—50a time lag from the produce of ^{14}C in the atmosphere by cosmic ray to the absorption by tree[20, 23], meanwhile the variations of ^{14}C in the atmosphere can be influenced by the upwelling of deep sea water[35]. Ice core record, therefore, was considered as a good way to solve the problem mentioned above[36]. In the early 1990s, the low-resolution Antarctic ice core record could not provide the answer to the nature of the solar activity during the Maunder Minimum[37]. Now, the high-resolution records of ice cores from the Greenland and the middle latitudes make it possible. In the ensuing sections of this paper, we try to answer the two questions relevant to the Maunder Minimum based on NO_3^- concentration in the Guliya ice core and polar ^{10}Be records. And in the latter section, the possibility of the existence of the periodicity of 36a in the solar activity will be discussed.

1 Data series of NO_3^- concentration in the Guliya ice core

During the 1990 through 1992, a Chinese-American Scientific Expedition Team investigated the Guliya Ice Cap (35°17′N, 81°29′E), the West Kunlun Mts., for several times. Eight ice cores were retrieved from that Ice Cap, among which the longest one, drilled at 6200 m a.s.l., was 308.6 m, and its time span was more than 700 ka[13, 38]. Until now, lots of research results about this deep ice core have been published[1, 13, 18, 19, 38—41].

We depended mainly on the seasonal characteristics of dust and $\delta^{18}O$ to date the upper part of this

308.6-m-long ice core[39]. According to the dating and the NO_3^- concentration along this ice core, annually variations of NO_3^- concentration were reconstructed in recent 1500 years[19]. It was found that there was a good positive relationship between NO_3^- concentration and the solar activity[18, 19]. Here, the data of NO_3^- concentration in the interval of 1545 through 1745 AD (see fig. 1) were selected for studying the state of the solar activity during the Maunder Minimum.

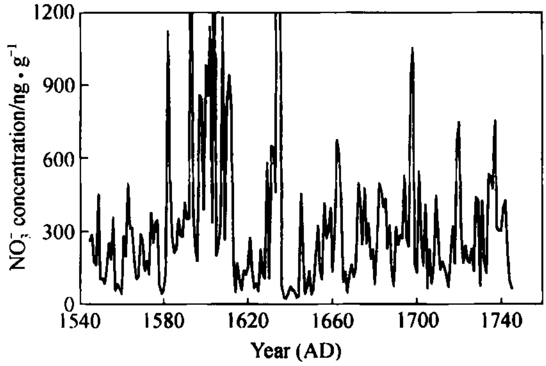

Fig. 1. Annually variations of NO_3^- concentration in the Guliya ice core in the period of 1545 through 1745 AD.

2 Existence of the Maunder Minimum

Fig. 1 shows that NO_3^- concentration, in general, was low during the 17th century, but its fluctuations were large, which hinders us to exactly tell the period with low concentration. The better way to distinguish the low concentration period is to use the long-term trend curve of NO_3^- concentration. In fig. 2(a), the secular trend curve of NO_3^- concentration is the quintic polynomial fitting curve for the data series of the middle value of five points of NO_3^- concentration. This fitting curve is consistent with the enveloping trend of the original NO_3^- concentration. Therefore the long-term trend of the solar activity could be revealed on the basis of this curve. Used the mean NO_3^- concentration, 263.6 ng/g, as a divide between the strong and the weak solar activity, it is clear that the sun was weak in the period of 1641 through 1710 AD (fig. 3). This period is just the right Maunder Minimum called by Eddy.

The solar activity strongly influences the flux of cosmic ray into the Earth atmosphere, and then results in the changes in cosmogenic isotope production rate in the atmosphere. When the sun is strong, the intensified solar magnetic field increases its shielding effect on cosmic ray, this leads a decrease in flux of cosmic ray into the Earth atmosphere, and then cosmogenic isotope production rate slows down; and *vice versa*. Thus, the changes in concentrations of cosmogenic isotopes, such as ^{10}Be and ^{14}C, recorded in deposits and tree ring, can tell us much information about the past sun. However, ^{10}Be, with the half-life as long as about 1.5×10^6 a, is produced in the atmosphere by the interaction of high-energy cosmic ray primaries and secondaries with nitrogen and oxygen, and only stays in the atmosphere for about 1—2 a because it usually adheres to aerosols and precipitates to the surface of the earth by means of wet and dry depositions; and ^{14}C, with the half-life about 5.73 ka, is produced in the atmosphere by the interaction of neutrons formed by cosmic ray in air with nitrogen, and usually keeps in the air and ocean for about several decades before it is absorbed by trees. Considered its geochemical behavior, ^{10}Be recorded in deposits can extend our knowledge about the solar activity back very far, and also can provide much information about the periodicities of the solar activity. These have been verified by ^{10}Be in the polar ice[42—44]. Fig. 2(b) illustrates the variations of ^{10}Be concentration in the Greenland ice[45], and its long-term trends in different ice cores are similar to that of NO_3^- concentration in the Guliya ice core. The high ^{10}Be concentration in the late 17th century is attributed to the weak sun, this also indicates that the Maunder Minimum was true. In the light of the time lag of $\Delta^{14}C$ in tree ring to ^{14}C produced in air, high value of $\Delta^{14}C$ in tree ring (see fig. 2(c)) in the late 17th century and the early 18th century is the further proof of the existence of the Maunder Minimum[23].

The charged particles from the sun are accelerated when they move along the lines of the geomagnetic force, and then enter into the atmosphere and collide with air molecules, and make them ionized or excited. When the excited molecules go back to their ground state, lights with special wavelengths are emitted by radiation. The lights of these kinds have colour, and form aurora. Because the flux of the charged particles from the sun is related with the solar activity, the frequency of auroral occurrence is usually regarded as a proxy of the solar activity. The auroral data from the world[34] are plotted in fig. 2(d), which also indicates the existence of the Maunder Minimum. As to the auroral data

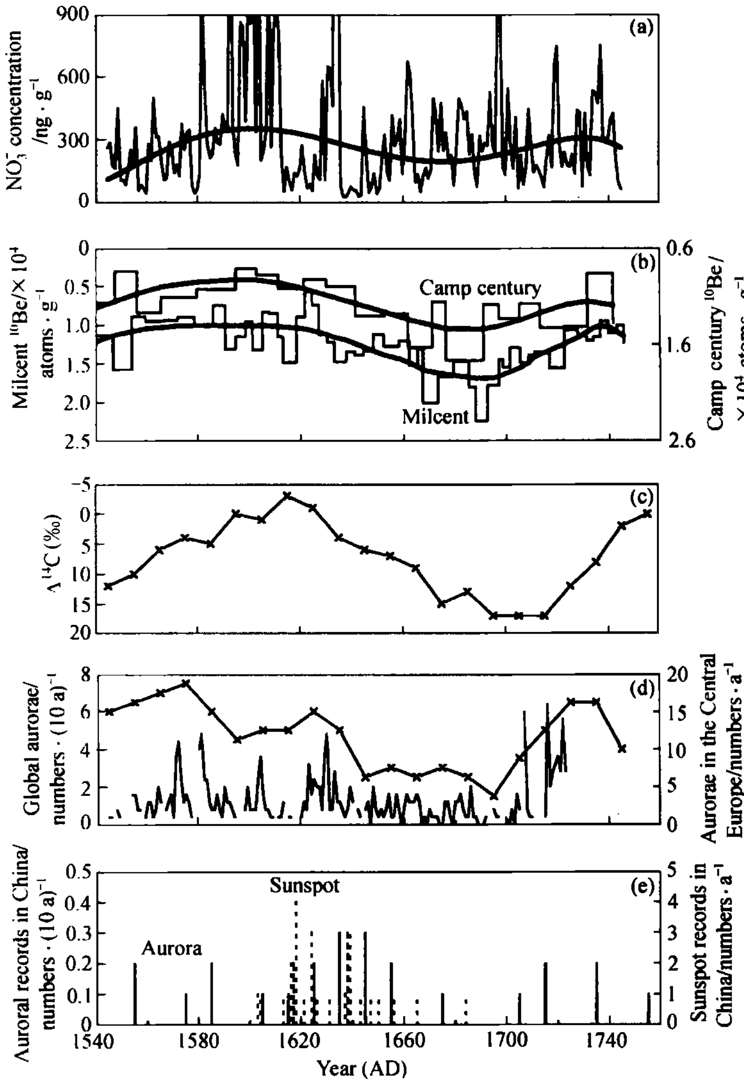

Fig. 2. Comparison of the variations of the proxies of the solar activity. (a) NO_3^- concentration in the Guliya ice core; (b) ^{10}Be concentration in polar ice[45]; (c) Δ^{14}C in tree ring[23]; (d) auroral data from the world[34] and the Middle Europe[46] (—×—, global; ——, Europe); (e) sunspot (······) and auroral (——) data from China[21, 47].

from the central Europe[46], their enveloping trend is similar to the curve of the worldwide auroral data (see fig. 2(d)). It is emphasized that the aurora can be observed in the middle latitudes when the sun is strong. Fig. 2(e) shows the numbers of aurorae and sunspots observed in China[21, 47]. We put the data of these two kinds together to avoid the influence of their insufficient records. This presents that the numbers of aurorae and sunspots were relatively small in the late 17th century, which provides another evidence for the existence of the Maunder Minimum.

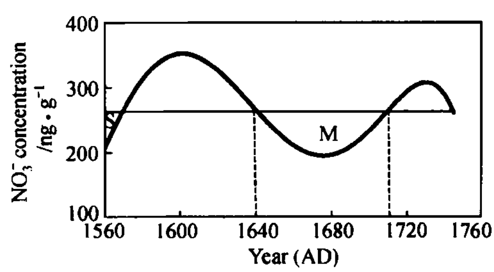

Fig. 3. The Maunder Minimum (marked by M) revealed by the trend curve of NO_3^- concentration in the Guliya ice core. The S represents the Sporer Minimum.

3 The solar cycle during the Maunder Minimum

In order to avoid the influence of extreme values of NO_3^- concentration in some special years on identifying the periodicities in its variations, the data set of 3-point running average value of NO_3^- concentration was used here for spectral analyses. Fig. 4(a) shows the spectral analytical result of the NO_3^- concentration data from 1545 to 1745 AD, there are three major cycles with the significance of 0.05, i.e. 33.3 a, 22.2 a and 10.5 a, and the latter two of which are similar to the Hale and sunspot cycles respectively; however, fig. 4(b) is for the NO_3^- data during the Maunder Minimum, there are also three remarkable cycles with the significance of 0.05, i.e. 11.7 a, 35 a and 17.5 a, the first significant cycle of which is identical with the sunspot cycle. All these indicate that the sunspot cycle existed during the Maunder Minimum.

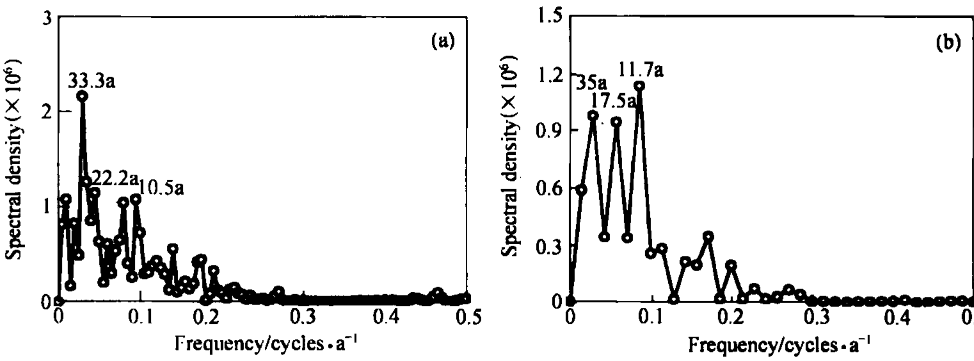

Fig. 4. The spectral analytical results of NO_3^- concentration in Guliya ice core. (a) The results for the data series from 1545 to 1745 AD; (b) for the data series from 1645 to 1715 AD.

Recently, the high-resolution record of ^{10}Be in polar ice displayed a notable cycle of about 11 a during the Maunder Minimum[43]; analytical results of auroral data also expressed that the sunspot cycle was normal in that Minimum[46, 48]. In the early European publications, observation of the sunspot in the late 17th century was documented, and it was found that solar peaks appeared evident in 1661, 1671 and 1684AD and produced cycle lengths of 10 a and 13 a[9, 49, 50]. Those provide further proofs for the existence of the sunspot cycle of about 11 a during the Minimum.

4 Discussion

From fig. 4, it can be seen clearly that the length of the solar cycle was longer during the Maunder Minimum, 11.7a, than in the period of 1545 to 1745 AD, about 10.5 a. Why this phenomenon occurred? Friis-Christensen and Lassen supposed that the length of the solar cycle is an indicator of the solar activity, and high solar activity implies short solar cycles whereas long solar cycles are characteristic of low activity levels of the sun[51]. In recent years, stellar activity cycles with periods ranging in length from about 7 to 20 a, similar to the changes in the length of the sunspot cycle, have been detected in most solar-like stars (those stars similar to the sun in mass and age)[9]. A most important finding was that there is an inverse relation between the stellar activity cycle length and average activity level[52], which not only provides a physical basis for the above-mentioned hypothesis advanced by Friis-Christensen and Lassen, but also demonstrates the longer length of the solar cycle during the Maunder Minimum expresses that the solar activity was low then.

The above spectral analytical results, together with the results gained before[18, 19], indicate that besides the cycle of about 11a, another cycle of about 33a are relatively stable in the variations of NO_3^- concentration in Guliya ice core, which implies that the solar activity maybe have a cycle of more than 30a when admitted NO_3^- concentration can reflect the information of the sun variability. Here again we investigate the variations of the proxies of the solar activity. Owing to the fact that the length of the sunspot cycle can represent the solar activity, its variations in recent 2000 years were reconstructed based on the estimation for the maximum and minimum years of the sunspot by Schove[53]. Fig. 5 plots the variations of the length of the sunspot cycle from 1540 to 1745 AD. It exhibits an obviously rhythmical change, with a cycle of average about 36 a (ranging from 28 to 42 a). Moreover, spectral analyses of the data of the length of the sunspot cycle in different intervals in recent 2000 years also show that the cycle of about 36 a was relatively stable. The geomagnetic activity is forced by the solar wind, thus its index can be regarded as a proxy of solar activity. The aa index, given by Mayaud according to the roughly antipodal observations in Greenwich and Melbourne, and eliminating the diurnal and seasonal variations of the geomagnetic activity, is a useful tool for describing the global geomagnetic activity[54]. A significant positive relation was found between the aa index and the sunspot number[54]. Spectral analysis of the variations of the aa index since 1868 AD shows that, besides the significant cycle of 11.1 a, another cycle of 28.6 a is also significant[48], and places in the scope of the cycles of the changes in the length of the sunspot cycle, ranging from 28 a to 42 a. A study pointed out that the variations in frequency of the auroral occurrence during the period of 1500 to 1948 AD exhibited a significant cycle of about 33.3 a[48]. From those facts, we realize that the solar activity has the cycle of about 36 a possibly.

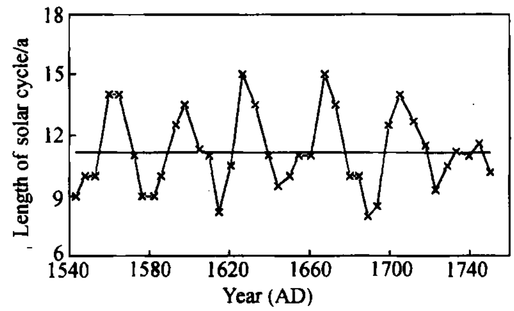

Fig. 5. Variations of the length of the sunspot cycle from 1540 to 1745 AD.

5 Conclusion

Through the above comprehensive analyses, we can conclude that during the Maunder Minimum, the sun was weak, but it was active with the sunspot cycle.

A 36 a cycle has been figured out from floods of hydrological, meteorological and glacier fluctuation data, and called Bruckner cycle. For a long time past, the cause of this ubiquitous cycle has not been found, although a study pointed out that the ocean-atmosphere interaction was responsible for this cycle exhibited in precipitation records in East China[55]. From the above analyses for the proxies of the solar activity, we found that the solar activity maybe contains the cycle with periods ranging from 28 a to 42 a, averaging 36 a, which is related to the changes in length of the sunspot cycle. This finding is of importance for the study of the relationship between the sun variability and the Earth climate change.

Acknowledgements We are grateful to Prof. Yao Tandong from Laboratory of Ice Core and Cold Regions Environment, Cold and Arid Regions Environmental and Engineering Research Institute, CAS, for his comments on the manuscript. Special thanks are given to Prof. J. Beer from Swiss Federal Institute of Environmental Science and Technology, for his providing us ^{10}Be data in polar ice. This work was supported by the Chinese National Basic Research Programme and CAS' Qinghai-Tibetan Project (Grant Nos. G1998040802, KZ95T-06 and KZ951-A1-204-02) and the National Natural Science Foundation of China (Grant No. 49801004).

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(Received May 16, 2000)