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Heliospheric modulation of cosmic rays and solar activity during the Maunder minimum

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Abstract. Modern models and direct cosmic ray experiments deal with heliospheric modulation of cosmic rays only during the recent times of rather high overall solar activity level. On the other hand, the question of cosmic ray modulation during the exceptional conditions of very quiet heliosphere is important. In the present paper we compare the variations of cosmic ray intensity with solar and auroral activity during the Maunder minimum (1645-1715) when the Sun was extremely quiet. We use the newly presented group sunspot number series as a measure of early solar activity, the auroral observations in central Europe as an indicator of transient phenomena in the inner heliosphere, and the radiocarbon data as a proxy of cosmic ray intensity. We find that both cosmic ray intensity and auroral activity closely follow the dominant 22-year cyclicity with sunspot activity during the Maunder minimum. Moreover, the strict antiphase between the 22-year variation of cosmic ray intensity and sunspot activity suggests that the 22-year variation in cosmic ray intensity can be explained by the diffusion-dominated terms of cosmic ray modulation without significant drift effects. We also discuss the possible origin of the behavior of the ^{10}Be data which is different from all other parameters during the Maunder minimum.

1. Introduction

During the last decades many efforts have been undertaken to study the dependence of the heliosphere and cosmic rays (CR) on solar activity. Sophisticated theories of cosmic ray modulation supported by space and ground-based experiments have been developed (see, e.g., rapporteur review by *Jokipii and Kotá* [1998]). The period of direct experimental studies of cosmic ray modulation is relatively short: The first regular ground-based ion chamber experiments started in the mid-1930s, and routine registration of cosmic ray intensity by the world neutron monitor network started in the mid-1950s followed soon by spaceborne detectors. During this period, relationships between solar activity, heliosphere, and cosmic rays have been studied intensively. However, it is important to know if the relationships found for these last few decades can be extrapolated backward to much earlier times.

In order to study cosmic ray intensity in early times when no direct CR measurements were made, one can only use different proxies of cosmic ray intensity. Natural archives of cosmogenic isotopes, such as ^{14}C and ^{10}Be, produced by cosmic rays in the Earth's atmosphere, are commonly used for this purpose. Unlike direct CR observations, proxy data have typically a more limited time resolution, and they depend on cosmic ray intensity only indirectly through complicated mechanisms of transport, precipitation, and storage. This makes it difficult to study the past CR modulation in great detail. However, a general anticorrelation between cosmic ray intensity and solar activity has been proven [*Stuiver and Quay,* 1980; *Beer et al.,* 1990; *Stuiver and Braziunas,* 1998] for the last 250 years covered by the Wolf sunspot numbers. This suggests that the CR modulation was fairly similar during this period (of direct solar observations but indirectly reconstructed CR intensity) to that of nowadays. We note that the overall level of solar activity was quite high during this period. However, the Sun's history knows periods of very low solar activity, so-called great minima, when visible sunspot activity nearly disappeared. The most recent great minimum was the Maunder minimum (MM) in 1645-1715 [*Eddy,* 1976]. It is known since recently that sunspot activity during MM was, contrary to the times of high solar activity, dominated by a 22-year cyclicity [*Usoskin et al.,* 2000]. Also, the solar wind and geomagnetic activity were abnormally weak during this great minimum [*Mendoza,* 1997; *Cliver et al.,* 1998].

Accordingly, it is possible that the CR modulation was rather different during MM than in the present times of high solar activity. Therefore it is important

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to study CR modulation during the Maunder minimum to better understand the modulation processes during very quiet solar conditions. We would also like to note that the analysis of recent cycles shows a rather unusual CR modulation during solar cycle 20, which was the lowest cycle since the beginning of regular CR measurements in the 1930s [see, e.g., *Webber and Lockwood,* 1988; *Usoskin et al.,* 1998]. This suggests that the modulation may be different during normal (high) and low solar activity periods.

Earlier studies of solar activity during the Maunder minimum used either a continuous series of indirect proxies like auroras [*Schove,* 1955] or a fragmentary series of direct sunspot observations [e.g., *Waldmeier,* 1960]. The newly invented series of group sunspot numbers [*Hoyt and Schatten,* 1998] compiles all available archival records of direct sunspot observations performed since the first observations by G. Galilei in 1610. This new series covers more than 95% of the days during the Maunder minimum [*Hoyt and Schatten,* 1996]. In the present paper we study the relationship between cosmic ray intensity, inner heliospheric transient phenomena, and the sunspot activity during the Maunder minimum. In section 2 we discuss the main features of sunspot activity during the Maunder minimum, as represented by the group sunspot number. Section 3 is devoted to the analysis of indirect proxies of the inner heliospheric transient phenomena (auroras) and cosmic ray intensity (cosmogenic isotopes ^{14}C and ^{10}Be) during MM. We discuss the results obtained on the characteristics of cosmic ray modulation during the Maunder minimum in section 4 and present our conclusions in section 5.

2. Sunspot Activity

The group sunspot number series (called R_g) by *Hoyt and Schatten* [1998], which is based on a large set of archival records, is more correct and homogenous than the Wolf [*Waldmeier,* 1960] or Schove [*Schove,* 1955] sunspot number series [*Hoyt and Schatten,* 1998; *Letfus,* 1999]. Sunspots appeared only rarely and seemingly sporadically during the deep Maunder minimum in 1645-1700. Fortunately, more than 95% of the days of this period were covered by direct sunspot observations [*Hoyt and Schatten,* 1996]. On the other hand, sunspots appeared only rarely, approximately 2% of time, and seemingly sporadically during this time. While standard time series analysis methods fail with such sparse data series [see, e.g., *Frick et al.,* 1997], we recently suggested a special technique to study sunspot activity during MM [*Usoskin et al.,* 2000]. This method is briefly described in the following (for more details, see *Usoskin et al.* [2000]). Since all R_g values during MM are small and not exactly known, we only use the information as to whether a sunspot has been reported

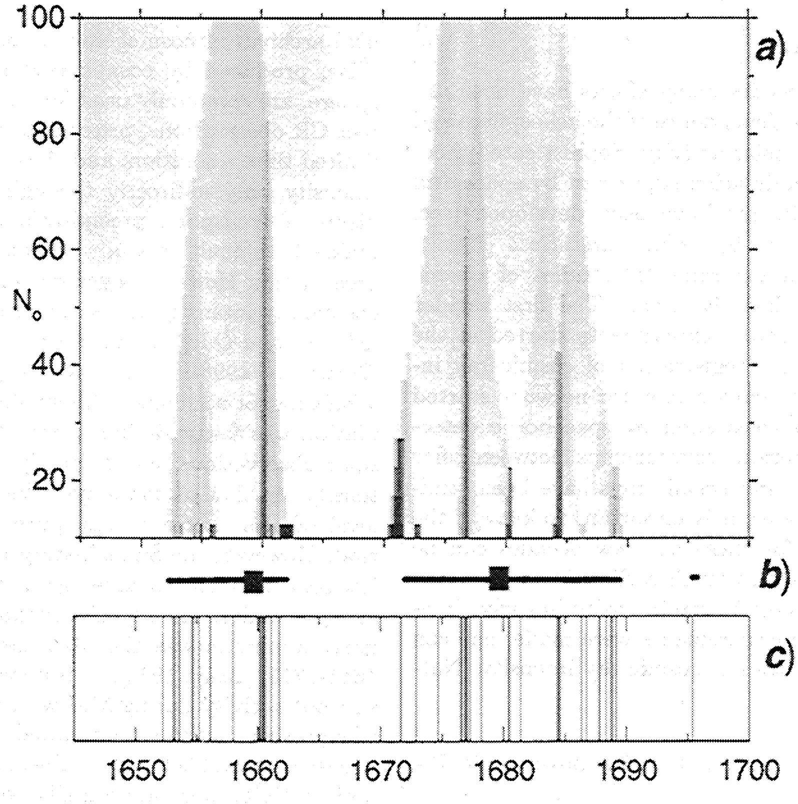

Figure 1. Occurrence of sunspot days during the deep Maunder minimum. (a) Map of concentration of sunspot days during the Maunder minimum for different N_o (see text). (b) Intervals of sunspot occurrence (horizontal bars) with the mass centers of the corresponding intervals (solid rectangles). (c) Sunspot days during the deep Maunder minimum.

on a certain day or not. (Note that *Harvey and White* [1999] analyzed similarly the distribution of days with sunspots versus spotless days when studying sunspot activity during the recent solar minimum.) The days with observed sunspots during the deep MM are shown as vertical bars in Figure 1c. We study the concentration of sunspot days as follows: Starting from day T_o, one can find the day T_1 so that there are exactly N_o sunspot days during the interval $[T_o, T_1]$ (N_o being fixed). The average concentration of sunspot days within the interval $[T_o, T_1]$ is then $P = N_o/(T_1 - T_o + 1)$. This value P is associated with the average date (so-called mass center) of sunspot days within the time interval $[T_o, T_1]$. Then one slides the starting time T_o and repeats the calculation, obtaining in this way a set of $P(t)$ and mass centers for a given N_o. The resulting map of $P(t, N_o)$ is shown in Figure 1a. Despite the sparse appearance of sunspots the time distribution of their occurrence shows a dominant, highly significant 22-year cyclicity. The sunspots during the deep MM are concentrated in two time intervals (shaded domains in Figure 1a) in 1652-1662 and 1672-1689. (Outside these intervals only one sunspot group in 1695 appeared.) These periods with the corresponding mass centers in 1658 and 1679-1680 are denoted in Figure 1b. Together with the sunspot maxima before (1639-1640) and after (1705) the deep Maunder minimum, this implies a dominant 22-year periodicity in sunspot activity during the Maunder minimum. The 22-year cyclicity also appears as long spotless periods in 1645-1651, 1662-1671, and 1689-1695. The fine structure within the two main sunspot intervals (Figure 1a) and the weak activity in 1695 suggest a possible subdominant 11-year cyclicity especially at the end of the Maunder minimum [*Ribes and Nesme-Ribes,* 1993; *Mendoza,* 1997; *Usoskin et al.,* 2000]. The years of sunspot occurrence maxima in and around the Maunder minimum are given in Table 1. Table 1 lists the maximum years according to the Wolf sunspot series [*Waldmeier,* 1960], yearly group sunspot number series [*Hoyt and Schatten,* 1998], our analysis [*Usoskin et al.,* 2000], and an analysis by *Mendoza* [1997] using sunspot observations by the French School of Astronomy [*Ribes and Nesme-Ribes,* 1993]. The years obtained by these different groups are quite close to each other.

Table 1. Years of Solar Activity Cycle Maximum

W[a]	HS[b]	Us[c]	Mc[d]	Bc[e]
1615	1613	1614	-	1615
1626	1625	1626	-	1627-1630
1639	1639	1640	-	1644
1649	1652	1654	-	1655
1660	1660	1660	1662	1668
1675	1676	1677	1676-1678	1679
1685	1684	1684	1684	1689-1690
1693	1695	1695	1695	1701
1705	1705	1705	1705	1709
1718	1719	1720	-	1720
1727	1728	1729	-	1731
1739	1739-41	1739	-	1740

[a] *Waldmeier* [1960].

[b] Years of maxima of yearly group sunspot number series [*Hoyt and Schatten,* 1998].

[c] *Usoskin et al.* [2000].

[d] *Mendoza* [1997].

[e] *Beer et al.* [1998].

3. Indirect Proxy Data

3.1. Auroras

Auroras are a proxy of geomagnetic activity caused by transient heliospheric phenomena, in particular coronal mass ejections and high-speed solar wind streams. A good review of auroral production and ancient auroral observations is given by *Silverman* [1992]. It was shown by Silverman that the occurrence of auroras at midlatitudes closely follows sunspot activity both over the solar cycle and over longer time intervals (secular cycle and great minima). Since the occurrence of auroras at midlatitudes requires strong magnetic disturbances, this series reflects major heliospheric transient irregularities. Although the 11-year cycle is dominant in the auroral series during normal solar activity times, the spectral analysis of the auroral record shows no evidence for 11-year cyclicity for Maunder minimum [*Silverman,* 1992]. Instead, peaks with longer periods of approximately 19-20 years, 25 years, and 15 years (see Figures 11 and 12 of *Silverman* [1992]) were found in the power spectrum for a period covering MM and some time before or after it.

We present the 5-year running average of auroral activity in central Europe according to *Křivský and Pejml* [1988] in Figure 2a. Auroral activity was quite low (0-4 auroras per year) during the Maunder minimum, in accordance with the suppressed solar activity. One can see that periods of increased auroral activity agree fairly well with sunspot occurrence during the Maunder minimum denoted by horizontal bars in the figure. Times of more frequent auroral occurrence are close to the mass centers of the corresponding sunspot occurrence intervals in approximately 1658, 1680, and 1705. This implies that there is a dominant 22-year cycle in auroral activity during the Maunder minimum which is in phase with the similar pattern in sunspot activity. It is also interesting to note that a small peak in auroral series took place in 1695, corresponding to the isolated sunspot group observed at that time and giving additional evidence for a subdominant 11-year cyclicity at the end of MM. Accordingly, the time behavior of auroral occurrence in central Europe, and, hence, of the major transient irregularities in the inner heliosphere, is in a good agreement with sunspot activity during the Maunder minimum.

Another series of auroral occurrence in middle Europe, during MM is depicted in Figure 2b according to Table 2 of *Schröder* [1992]. This series clearly shows a behavior during MM very similar to the other auroral series shown in Figure 2a [*Křivský and Pejml,* 1988] with a dominant 22-year cyclicity and a possi-

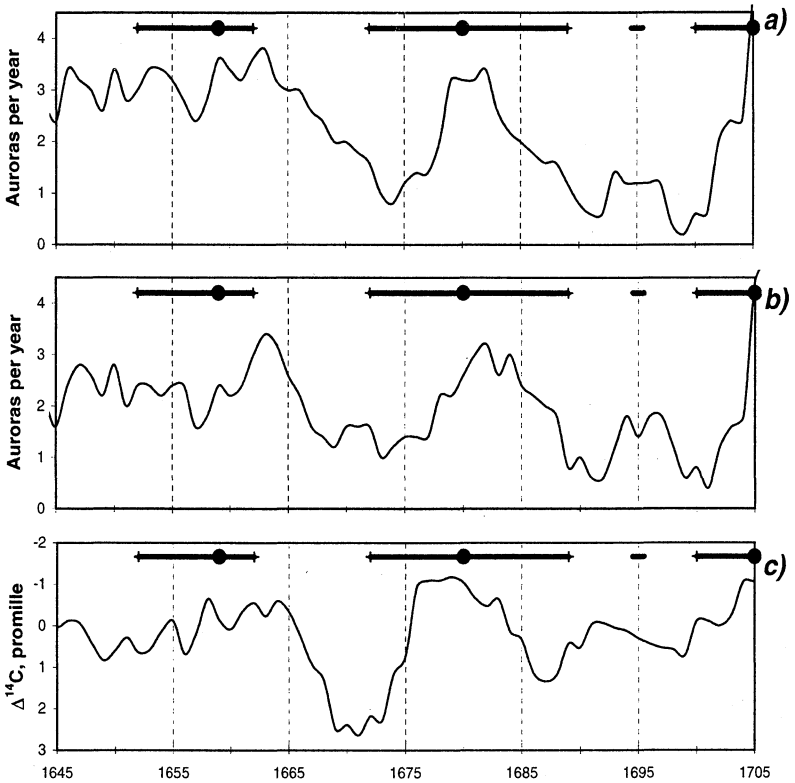

Figure 2. Data on different proxies during the Maunder minimum: (a) 5-year running averaged number of auroras per year in central Europe according to *Křivský and Pejml* [1988]; (b) 5-year running averaged number of auroras per year in central Europe according to *Schröder* [1992]; and (c) 5-year running average abundance of radiocarbon in tree rings [*Stuiver and Braziunas*, 1993]. Horizontal bars denote periods of sunspot occurrence, and solid circles denote the times of the mass centers of the corresponding periods.

ble weak 11-year cyclicity at the end of MM. Our fast Fourier transform analysis of this series for 1640-1715 yields peaks at periods of 3-4 years and 20-25 years with only a small power around 11 years. Without a detailed analysis, *Schröder* [1992] concluded the existence of 11-year cyclicity during MM. However, the present analysis shows that both auroral series confirm the conclusion of a dominant 22-year variation in auroral occurrence in central Europe, in accordance with *Silverman* [1992].

3.2. Cosmogenic Radiocarbon ^{14}C

Radiocarbon ^{14}C (half-life 5730 years) is a proxy of galactic cosmic ray intensity in the neutron monitor energy range. Radiocarbon is produced by the capture of a thermal neutron by atmospheric nitrogen: $^{14}\mathrm{N}(n,p)^{14}\mathrm{C}$. Thermal neutrons are produced in atmospheric nucleon cascades caused by cosmic ray particles in the atmosphere. Radiocarbon, oxidized to carbon dioxide, experiences different processes of atmospheric circulation and reservoir exchange and is finally stored in natural archives like tree rings. The fact that radiocarbon abundance variations (Δ^{14}C) reflect the solar modulation of cosmic rays is known since long [e.g., *Damon et al.,* 1978, and references therein]. Changes of the geomagnetic field and climatic effects also play a role in radiocarbon production and deposition [e.g., *Damon et al.,* 1978], especially on the long-term scale. During times of normal solar activity level, Δ^{14}C variations demonstrate a clear 11-year cycliclity anticorrelated with sunspot activity with a time lag of 2-3 years and a cross-correlation coefficient of about −0.65 [e.g., *Stuiver and Braziunas,* 1998]. The period of Maunder minimum is clearly seen as an increase in Δ^{14}C record [*Stuiver and Quay,* 1980], implying increased cosmic ray intensity at this time. *Peristykh and Damon* [1998] made a spectral analysis of the annual Δ^{14}C series presented by *Stuiver and Braziunas* [1993] and showed that, while the 11-year cycle is prominent throughout the periods of 1540-1630 and 1715-1805, it is suppressed during the Maunder minimum. Instead, they found a dominant 22-year cyclicity in this Δ^{14}C series during the Maunder minimum, following the idea first suggested by *Kocharov* [1988]. They also estimated that the possibility of a climatic origin of this 22-year variation in Δ^{14}C is very low and concluded that the 22-year cycle during the Maunder minimum is due to the similar cyclicity in the production rate, i.e., in cosmic ray intensity. The same conclusion of the dominance of 22-year cyclicity in the ^{14}C production rate during MM was obtained using an independent Soviet radiocarbon series [*Kocharov et al.,* 1995]. The comparison of the two radiocarbon series shows that they are mutually

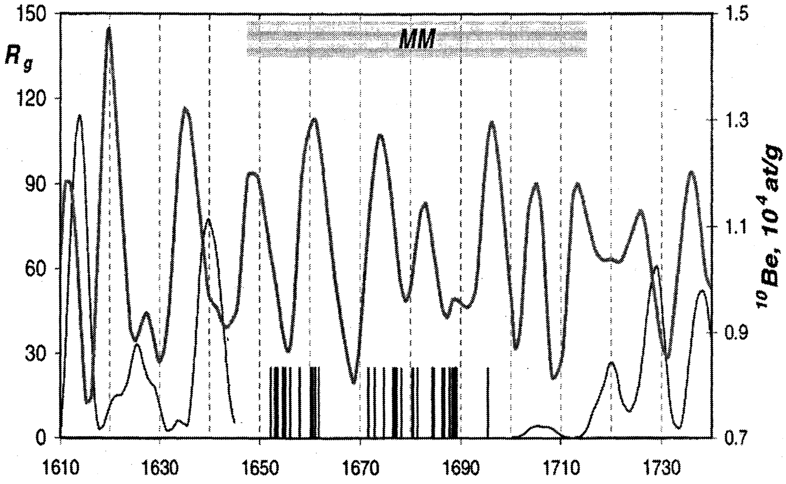

Figure 3. Comparison of ^{10}Be data and sunspot activity. Filtered and 1.5-year-shifted ^{10}Be data (thick line; see Figure 2a of *Beer et al.* [1998]) and 30-month smoothed group sunspot number series (thin line). Individual sunspot days during the deep Maunder minimum (1645-1700) are shown as vertical bars. Maunder minimum (1645-1715) is marked with shaded area.

consistent during MM, thus verifying the conclusion of a 22-year cyclicity [*Damon et al.,* 1999].

So far, the phase of ^{14}C abundance variations during MM with respect to sunspot activity has not been studied. We analyze here the Δ^{14}C tree ring series [*Stuiver and Braziunas,* 1993] during MM. First, a binomial trend over the MM is removed from the data, and then a 5-year running average is calculated. The obtained Δ^{14}C time series during MM is shown in Figure 2c. This time series of radiocarbon abundance demonstrates an approximately 22-year cycle which is consistent with the simultaneous sunspot activity and auroral occurrence discussed above and shown in Figures 2a and 2b.

3.3. Cosmogenic Isotope ^{10}Be

Concentration of the long-lived cosmogenic isotope ^{10}Be (half-life 1.5×10^6 years) in polar ice is another proxy of galactic cosmic ray intensity. Cosmogenic ^{10}Be is produced in nuclear interactions of cosmic ray nuclei with atmospheric nitrogen and oxygen. After production, ^{10}Be is attached to aerosols and then precipitates to the ground. (Residence time in the atmosphere is 1-2 years [*Beer et al.,* 1990; *McHargue and Damon,* 1991].) The long-term behavior of ^{10}Be data shows, e.g., several great minima of solar activity [see, e.g., *McHargue and Damon,* 1991, and references therein]. On a short-term scale, ^{10}Be data show an 11-year cyclicity during times of normal solar activity anticorrelated with the sunspot cycle [*Beer et al.,* 1990; *Steig et al.,* 1996]. The time behavior of ^{10}Be data from Dye-3, Greenland, depicts a dominant, approximately 11-year cyclicity throughout the Maunder minimum [*Beer et al.,* 1998]. *Beer et al.* [1998] filtered the data with a 7-24-year band-pass filter and shifted the data by 1.5 years to compensate for the residence time of ^{10}Be in the atmosphere. We have reproduced this series of ^{10}Be concentration (in atoms per gram) in Greenland ice in Figure 3 after Figure 2a of their paper.

Let us now compare the ^{10}Be concentration and sunspot activity during and around the Maunder minimum. One can see in Figure 3 that ^{10}Be data show an 11-year variation which is in antiphase with sunspot activity before and after the Maunder minimum. However, the phase relation between the ^{10}Be concentration and sunspot activity is not straightforward during the Maunder minimum. Note first that the years of maximum ^{10}Be concentration (which are expected to correspond to solar activity minima) in 1661, 1674, 1683, 1696, and 1705 are very close to years of sunspot activity maxima presented in columns 1-4 of Table 1. Moreover, we have listed in Table 1 (column 5) the years of solar activity maxima, as reconstructed by *Beer et al.* [1998] from the minima of the ^{10}Be series (see Table 1 in their paper). In Figure 4 we compare the ^{10}Be-based reconstruction of sunspot maximum years with those obtained from the four estimates of maxima based on direct sunspot observations (columns 1-4 of Table 1). As seen in Figure 4 there is a systematic shift of 3-7 years between the ^{10}Be minima and sunspot activity maxima during the Maunder minimum. This implies that the ^{10}Be time series had indeed a different phase relation with solar activity during MM than at times of higher solar activity.

4. Discussion

We have shown that both auroral activity and Δ^{14}C variations demonstrate a dominant 22-year variation during the Maunder minimum with a possible weak 11-year cycle emerging at the end of the period. This agrees with the pattern of sunspot activity during the same period [*Usoskin et al.,* 2000]. Moreover, the phase of 22-year variation of auroral activity and Δ^{14}C agrees with that of sunspot activity: Periods of sunspot occurrence coincide with increased auroral activity and reduced Δ^{14}C (Figure 2). These three variables cor-

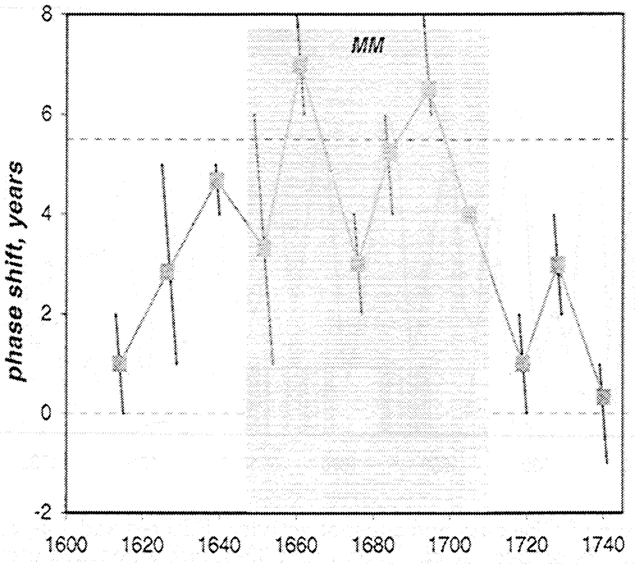

Figure 4. Average difference between the times of solar activity maxima as reconstructed by *Beer et al.* [1998] from ^{10}Be data (column 5 in Table 1) and the times of directly observed sunspot number maxima. Inclined bars denote differences in sunspot maximum times between different authors (columns 1-4 in Table 1).

respond to different processes: Sunspots reflect the toroidal component of the magnetic field in the solar convection zone, auroral occurrence at midlatitudes corresponds to strong heliospheric transients in the near-Earth space, and Δ^{14}C depends on cosmic ray intensity in the neutron monitor energy range. The good agreement between these three series found in this paper supports the view that the corresponding, rather different aspects of solar-heliospheric conditions were mutually consistent and had a common nature in the special behavior of the Sun during the Maunder minimum.

Different mechanisms are known to affect cosmic ray intensity at 1 AU. Some of them, i.e., diffusion, convection, and adiabatic energy losses in the outgoing solar wind carrying the interplanetary magnetic field (see, e.g., the review by *Fisk* [1979]), as well as the merged and corotating interaction regions [see, e.g., *Balogh et al.,* 1999], are independent of the polarity of the solar magnetic field. These effects dominate the heliospheric modulation of cosmic rays, leading to the known 11-year variation of cosmic ray intensity in antiphase with solar activity. Other effects are related to the drift of cosmic ray particles in the interplanetary magnetic field [see, e.g., *Jokipii and Levy,* 1977; *Fisk et al.,* 1998] and thus depend on the particle's charge state and the polarity of the solar magnetic field. The drift effects lead to a 22-year cyclicity in CR modulation which is seen, e.g., in the difference of shape between odd and even cycles of cosmic ray intensity. The drift mechanism is enhanced during periods of low to moderate solar activity, i.e., around solar cycle minima, especially during negative helicity minima, i.e., for $qA < 0$ [see, e.g., *le Roux and Potgieter,* 1995]. Cosmic ray particles can use the flat heliospheric neutral sheet to enter inner heliosphere during negative helicity minima [e.g., *Kotá and Jokipii,* 1983]. On the other hand, during positive helicity times the drift sweeps cosmic ray particles outward along the neutral sheet.

Solar wind speed and interplanetary magnetic field strength were weak during MM, reducing the size of the heliosphere at this time [*Mendoza,* 1997; *Cliver et al.,* 1998]. As a consequence, the overall level of cosmic ray intensity was higher than during normal solar activity times [*Stuiver and Quay,* 1980]. Also, the suppressed auroral activity and the absence of visible solar corona [*Eddy,* 1976; *Cliver et al.,* 1998] during MM imply that heliospheric transients were quite rare. Under such conditions of an extremely quiet Sun, especially during the deep Maunder minimum, the amplitude of CR modulation was smaller than during normal solar activity times.

The extremely quiet solar behavior resulted from the fact that the 11-year cyclicity nearly vanished during MM, leaving the 22-year cyclicity as the dominant variation during MM. We would like to note that the 22-year variation is a persistent feature in sunspot activity over the whole 400-year time interval of direct sunspot observations [*Mursula et al,* 2000] and reflects the existence of a small relic dipole moment in the Sun [*Cowling,* 1945]. During the present high-activity cycles the 22-year variation forms only some 10% of sunspot activity [*Mursula et al,* 2000], but during MM it was the dominant form of sunspot variability. Following the behavior of sunspot activity, the CR intensity depicted a dominant 22-year variation during the Maunder minimum. This is confirmed by the similarity of the variations in radiocarbon series, auroral occurrence, and sunspot activity during MM (see Figure 2). This similarity suggests that the global heliospheric conditions mainly varied with 22-year cyclicity rather than with

11-year cyclicity during MM. Accordingly, the 22-year modulation of cosmic rays during MM can be explained by those mechanisms, like diffusion and convection, that depend on solar activity level. This is a new explanation for the 22-year variation of CR intensity during MM. Earlier papers have suggested that the 22-year variation in CR intensity during MM is due to the drift mechanism [*Jokipii,* 1991; *Peristykh and Damon,* 1998]. Of course, both mechanisms may be at work, but the present study shows that the diffusive mechanisms alone are sufficient to cause the found 22-year modulation.

While the above scenario is consistent with sunspot, auroral, and Δ^{14}C observations, the existence of roughly 11-year cyclicity in ^{10}Be concentration during MM disagrees with it. However, we have shown above that the phase between ^{10}Be variations and sunspot activity changes dramatically from negative correlation during normal times to positive correlation during MM. Thus the variations in ^{10}Be during MM hardly reflect variations of galactic cosmic ray intensity. Neither can the solar cosmic rays be assumed to form the source of these in-phase variations because this would require an extremely high flux of solar cosmic rays, contradicting the low sunspot activity during MM. Leaving this question to a detailed analysis by experts in atmospheric transport and deposition of ^{10}Be, we briefly present our view of what might cause the observed variation in ^{10}Be data during MM. While the production of ^{10}Be is directly associated with CR intensity in the upper polar atmosphere, the precipitation, and hence the concentration in ice, strongly depends on local meteorological conditions [*Lal,* 1987]. This dependence is different from the abundance of Δ^{14}C, which reflects global rather than local CR intensity and global climate because of the transport and exchange between huge carbon reservoirs [*Damon et al.,* 1978].

The importance of local climatic effects for the ^{10}Be record is studied in literature to a large extent [see, e.g., *Lal,* 1987; *Beer et al.,* 1988; *Damon and Peristykh,* 1997]. The Maunder minimum coincided in time with the Little Ice Age with unusually low temperatures. During cold periods the rate of snow precipitation decreases, resulting in higher concentration of ^{10}Be in polar ice even for equal production rate [*Lal,* 1987]. The effect of local climate on the ^{10}Be record has been studied recently. The ratio of amplitudes of 11-year variation in ^{10}Be concentration between Greenland and the Antarctic varied by an order of magnitude during the last 60 years because of changes in local climate [*Steig et al.,* 1996]. Thus the local climate seems to influence the ^{10}Be concentration by ampifying or attenuating its variations [*Beer et al.,* 1990]. On the other hand, the amplitude of CR intensity variations was smaller during MM, leading to a smaller variation of the production rate. Therefore the role of local climate might be even enhanced during the Maunder minimum with respect to higher-activity periods. Usually, there is no notable correlation between ^{10}Be concentration and the δ^{18}O series, which is known to be a measure of local temperature. However, a correlation between ^{10}Be and δ^{18}O series was found for MM using ice samples from Camp Century, Greenland [*Beer et al.,* 1988]. This result gives further evidence that the ^{10}Be record was highly influenced by local polar climate during MM. Also, *Damon and Peristykh* [1997] noted that it is important to consider the accumulation rate of ^{10}Be with respect to the snow precipitation rate. Thus, while the record of ^{10}Be concentration in polar ice is a reliable proxy of CR intensity during normal activity times, the ^{10}Be series may be greatly distorted by climatic effects during the Maunder minimum.

5. Conclusions

Concluding, we have shown that the auroral occurrence and cosmic ray intensity as measured by Δ^{14}C depict a roughly 22-year variation during the Maunder minimum, in agreement with the 22-year variation in sunspot activity [*Usoskin et al.,* 2000]. The 22-year variation of auroral occurrence (radiocarbon level) was fairly well in phase (in antiphase, respectively) with sunspot activity. The very similar 22-year variation in the three different solar-heliospheric parameters (sunspot activity, auroral activity, and cosmic ray intensity) suggests a profound 22-year variation in the whole heliosphere during MM. The antiphase in 22-year variation between cosmic ray intensity and sunspot activity suggests that the 22-year variation in cosmic ray intensity was produced by the diffusion-dominated terms of cosmic ray modulation. Accordingly, the 22-year variation in cosmic ray intensity can be understood without a significant effect by the drift mechanism [*Jokipii,* 1991]. The short-term variation in ^{10}Be concentration disagrees with the dominant 22-year variation in the heliosphere during MM. However, we noted that the phase between ^{10}Be concentration and sunspot activity changed during MM, suggesting that other mechanisms, probably local climatic effects, may distort the direct solar driving of ^{10}Be by sunspot activity during the Maunder minimum.

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