Time Evolution of Solar Activity and Cosmic Ray Intensity during the Maunder Minimum

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Abstract

The strong anticorrelation between solar activity and cosmic ray intensity in recent times of an active Sun is well known. However, there is so far no direct evidence that this anticorrelation exists even during the great minima of solar activity. We study solar activity during the period of Maunder minimum (1645-1715) using the sunspot group number series presented recently by Hoyt and Schatten (1998). We find that the approximately 22-year Hale cycle dominated solar activity during this period. Earlier, the Hale cycle has been shown to exist in cosmic ray intensity (reconstructed from cosmogenic isotopes) during the Maunder minimum. Accordingly, the time variation and the dominant periodicities were essentially the same in solar activity and cosmic rays during this minimum. This also implies that the cosmic ray intensity records in natural archives are good proxies for the long-term behaviour of solar activity even during global minima.

1 Introduction

When studying the modulation of galactic cosmic ray (CR) intensity by solar activity (SA), three epochs can be distinguished. The first one, since the middle of this century, is the epoch of direct observations of cosmic rays by ground based neutron monitors and other devices. During this epoch, we can study the connection between the CR and SA in great detail, and it is known that the intensity as well as the energy spectrum of galactic cosmic rays are modulated by solar activity, and that variations of the CR flux are well anticorrelated with SA.

During the second epoch, since about the year 1700, direct and fairly continuous solar observations exist and sunspots are commonly used as an index of overall SA. However, no direct CR observations exist and the CR intensity is usually reconstructed by the method of cosmogenic isotopes (*e.g.* Stuiver and Quay, 1980; Kocharov *et al.*, 1985; Beer *et al.*, 1990). This method is based on the idea that the production rate of cosmogenic isotopes (such as ^{14}C and ^{10}Be) is determined by CR flux which, in turn, is modulated by SA. It has also been shown that the so reconstructed CR intensity is indeed in anticorrelation with SA during the recent times of an active Sun.

The third epoch is the time of indirectly reconstructed measures of CR intensity without regular solar observations. For this epoch the only way to study SA is by means of reconstructed CR intensity, assuming the CR-SA anticorrelation. Earlier studies (*e.g.* Kocharov *et al.*, 1995; Beer *et al.*, 1998) of the Maunder minimum used this approach since there were no regular SA series covering that period.

The new series of sunspot group (SG) numbers constructed by Hoyt and Schatten (1998) covers the period of Maunder minimum, moving that period from the third to the second epoch. In this paper we study the connection between SA and CR during the Maunder minimum.

2 Solar Activity during Maunder Minimum

Since sunspots appeared very rarely during 1645-1700 (see Fig. 1a), classical time series analysis methods do not work for this special period. (Therefore, e.g., the results of Frick *et al.*, 1997, using wavelet analysis of SG series, are not relevant for the Maunder minimum.) After the year 1700, sunspot groups appeared more regularly, though at a very low level, displaying a clear, roughly 11-year cycle (1700-1712) with maximum at around 1705. However, in this paper we concentrate rather to the period of 1645-1700 when the sunspot occurrence was very weak and irregular, and when the usual analysis methods do not work.

The exact number of sunspot groups observed on a single day during the Maunder minimum is not very reliable since the number of observers (with imprecise instrumentation) was small and sunspots appeared rarely. Under these conditions, the accuracy of determining the exact sunspot group numbers is reduced and, accordingly, the reported errors (Hoyt and Schatten, 1998) are large for these early observations. In order to reduce this "noise" we deal with the number of days with observed sunspot groups rather than with the sunspot group numbers themselves. When the exact number of sunspot groups in some time interval is very uncertain, it is of more fundamental and reliable information to know if a group of sunspots (or several) indeed appeared during that interval or not. Accordingly, when analyzing SA during the special part of Maunder minimum (1645-1700), we constructed from the daily SG series a new series of daily values $S(t)$, for which $S(t) = 1$ if there were sunspots observed on day t, and $S(t) = 0$ otherwise.

In order to study the occurrence of sunspot groups, we made use of a modified "sliding mean frequency" technique (Efremova *et al.*, 1997) which can briefly be described as follows. Starting from time t_o one can count the number of days with sunspots $I_o = \sum S(t)$ until $I_o = I^*$ at time t_1, where I^* has a fixed value. Then one repeats the calculations for the next interval starting from t_1 and finding t_2, so that $I_1 = I^*$ etc. Thereby the period under study is separated into intervals which contain an equal number of days with sunspot groups. Dividing the number I^* by the duration of the corresponding time interval, one obtains the sliding mean frequency of sunspot group occurrence within the interval $[t_i, t_{i+1}]$: $f_i \equiv I^*/(t_{i+1} - t_i)$. The error (68% confidence level) in determining the sliding mean frequency is: $\sigma_f/f = (I^* - 1)^{-1/2}$ (Efremova *et al.*, 1997). The sliding mean frequency of sunspot group occurrence is shown by solid line in Fig. 1a for $t_o = 1645$ and $I^* = 30$ ($f/\sigma_f \approx 5.4$), together with the monthly sunspot group numbers. This frequency gives the probability to see sunspot groups during a randomly chosen day within the $[t_i, t_{i+1}]$ interval.

Sunspot groups occurred during years 1652-1662 and 1672-1690 while no sunspots were reported during years 1662-1672 and 1690-1700 (see Fig. 1a). The mean frequency shows two large increases (1653-1661 and 1672-1689), depicting the dominance of a roughly 22-year periodicity. The second increase seems to be divided into the main (1676-1678) and secondary (1684-1689) peaks, suggesting for a possible Schwabe cycle. (This is true also for the monthly sunspot group numbers. Curiuosly, even the first large increase may have a similar two-peak structure). The years of maxima of SG data are summarised in Table 1. (The question mark in Table 1 means that the maximum is not significant). The main maxima are stable and their position varies only slightly with the start time t_o. Taking into account the previous maximum before the Maunder minimum at about 1640 and the next maximum at 1705, we conclude that the approximate 22-year periodicity existed in SA during the Maunder minimum, and the cycle lengths (between maxima) were 18 ± 3, 20 ± 4 and 27 ± 3 years.

A seemingly random occurrence of sunspots during that period can be explained by the model by Ruzmaikin (1997). According to this model, the total field in the convection zone, B, consists of two parts: the mean magnetic field, B_o, generated by the dynamo mechanism, and a randomly fluctuating magnetic field, b. If the total field, $B = B_o + b$, exceeds some threshold, a sunspot group (or groups) appears. Since the mean field is known to be lower than the threshold (see Ruzmaikin, 1997 and references therein), both of the components are important for sunspot activity. If one (most likely, the mean field B_o) or both of the components are reduced during a great minimum, the occurrence of sunspots would be rare and "random", although it would still have some periodicity in the occurrence probability. This is exactly the behaviour of SA we see for the Maunder minimum. Although the Maunder minimum continued until 1715, it seems that a slow recovery of the mean field already started at about 1700 (or even earlier), leading to a regular 11-year cycle of very low level (c.f. Fig. 1 by Ruzmaikin, 1997).

Table 1. Years of SA maxima and CR minima (from ^{14}C) during Maunder minimum.

Sunspot groups	1640	≈1654 (?)	1658-1661	1677-1681	1685-1689 (?)	≈1705
^{14}C data	≈1641	...	≈1662	≈1680	1693 (?)	≈1705

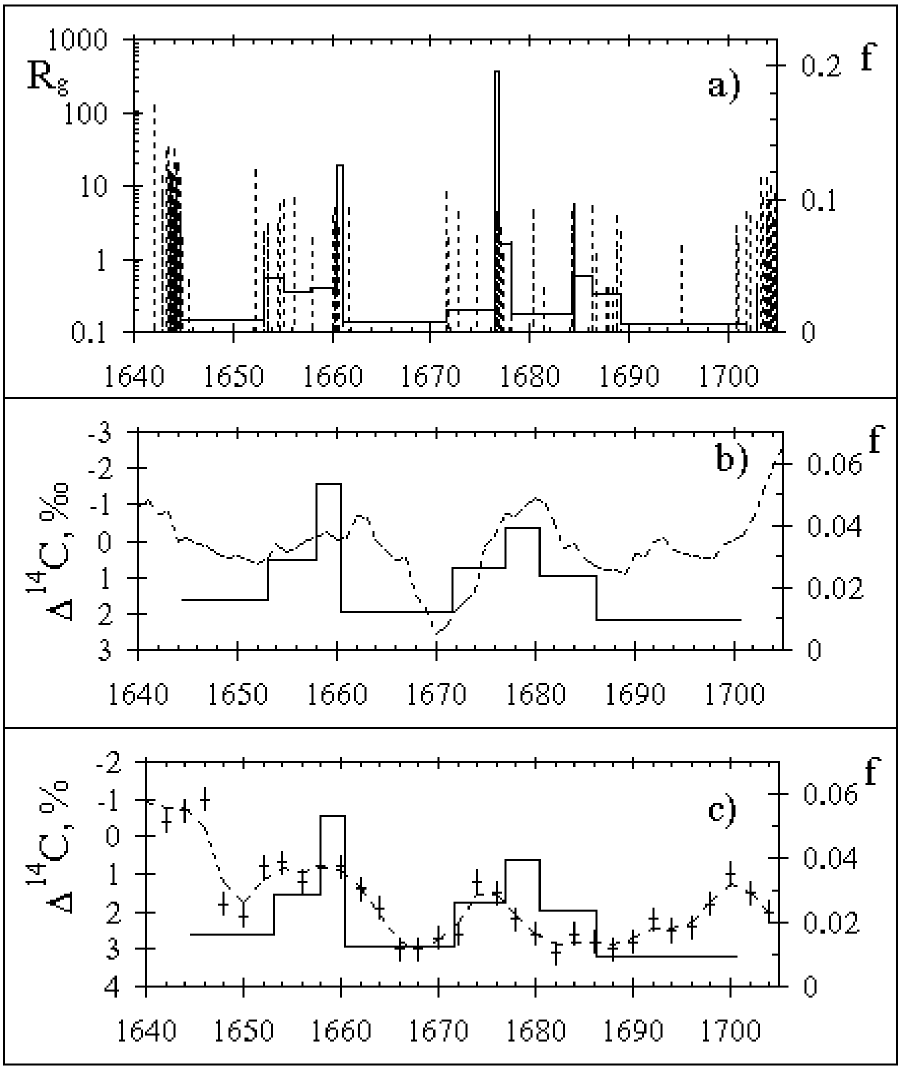

Figure 1.
a) Monthly sunspot group numbers (Hoyt & Schatten, 1998), *Rg*, (dashed bars) and sliding mean frequency of sunspots occurrence (I^*=30), *f*, (solid line) during the irregular part of the Maunder minimum;

b) Variations of radiocarbon content in tree rings (Stuiver & Braziunas, 1993), $\Delta^{14}C$, (dashed line) and sliding mean frequency of sunspots occurrence (I^*=50), *f* (solid line);

c) Variations of radiocarbon content in tree rings (Kocharov et.al., 1995), $\Delta^{14}C$,(dashed line and points) and sliding mean frequency of sunspots occurrence (I^*=50), *f* (solid line).

3 Cosmic Rays vs. Solar Activity

The inverted smoothed yearly $\Delta^{14}C$ series (Stuiver and Braziunas, 1993) with the global trend subtracted is shown in Fig. 1b for the Maunder minimum, together with the sliding mean frequency of sunspot occurrence (now with $I^* = 50$). A good agreement is evident when a time shift of a couple of years between the two series is taken into account (see also Table 1). (The weak peak of $\Delta^{14}C$ series in 1693 may correspond to the peak of SA in 1685-1689; see Table 1). Another set of ^{14}C measurements (Kocharov *et al.*, 1985) is shown in Fig. 1c, depicting the same periodicity pattern. Thus, dominant patterns of CR and SA time evolutions during the Maunder minimum correspond to each other. Note that it has been reported earlier (*e.g.* Kocharov *et al.*, 1995; Peristykh and Damon, 1998) that ^{14}C data (and therefore the CR intensity) demonstrates the Hale periodicity during the Maunder minimum while no reliable evidence for the presence of the 11-year Schwabe cycle was found for that period.

Data on the cosmogenic ^{10}Be isotope has been used for similar analyses. The most recent analysis of $^{10}Be\ Dye-3$ data (Beer *et al.*, 1990) for the Maunder minimum shows the presence of the Schwabe cycle (Beer *et al.*, 1998). Beer *et al.* (1998) band-pass filtered the data, trying to depress the Hale cycle in this way. However, an earlier analysis based on the same data set (Kocharov *et al.*, 1991) claimed the dominance of the Hale cycle during the Maunder minimum, with years of CR minima close to those in Table 1. Accordingly, it is not yet clear which cyclicity (Schwabe or Hale) dominated the ^{10}Be series during the Maunder minimum.

Concluding, we have shown that, although irregular and seemingly random, the sunspot group series introduced by Hoyt and Schatten (1998) demonstrates the Hale periodicity during the Maunder minimum. The behaviour of sunspot occurrence during this great minimum is in agreement with the model by Ruzmaikin (1997). The CR intensity reconstructed from cosmogenic isotopes, in particular from ^{14}C, shows a similar periodicity for the Maunder minimum. This would imply that the drift-dominated modulation plays the most important role during very weak levels of SA. For future studies of the solar modulation of cosmic rays in the past, in particular during the great minima, new records of cosmogenic isotopes and other CR reconstruction techniques would be very useful.

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