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LETTER

Letter to the Editor

Cyclic behaviour of sunspot activity during the Maunder minimum

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Abstract. We study the behaviour of sunspot activity in 1610-1750, i.e. just prior to, during and slightly after the Maunder minimum, using the new series of group sunspot numbers (Hoyt & Schatten 1998). We apply the delayed component technique and show that, while the transition from the normal cyclic evolution to the minimum was very abrupt, the recovery from the minimum was gradual, proceeding through a tiny but very regular cycle in 1700-1712 and a transition period with a phase catastrophe in 1712-1720. Exploiting the good coverage of the Maunder minimum by daily solar observations, we show that the sunspot ocurrence is concentrated, with a high statistical significance, to two intervals around 1658 and 1680. Together with the last sunspot maximum before the Maunder minimum in 1639/1640, and the maximum in 1705, this implies a significant, approximately 22-year periodicity in sunspot activity during the Maunder minimum.

Key words: Sun: activity – Sun: sunspots

1. Introduction

The question about the nature of solar activity during great solar minima, such as the Maunder minimum (MM) in 1645-1715 (Eddy 1976; Wilson 1994), is of great interest not only for solar physics but also for geophysical and heliospheric studies. The commonly used sunspot index series, the Wolf numbers series, does not cover MM. However, some studies of sunspot activity (SA) during the second half of MM have been performed earlier (Ribes & Nesme-Ribes 1993; Sokoloff & Nesme-Ribes 1994) using the routine solar observation by the French school of astronomy.

Recently, a new series of group sunspot numbers (GSN; see Fig. 1) was published (Hoyt & Schatten 1998). This series is based on a large set of archival records and provides reliable data on SA since 1610, covering hence the entire MM for the first time. Using this series it is now possible to make a detailed study of the behaviour of the Sun during MM. Frick et al.(1997) analyzed the monthly GSN values using the wavelet method, proving the dominance of the Schwabe cycle for the entire GSN interval except for MM. In this paper, we perform a detailed analysis of SA using GSN data for the years 1610-1750, covering the time slightly before and after MM, as well as the minimum time itself. Using the delayed component method, we study the phase space evolution of solar cycles around the MM. Also, we examine the question whether the remnant activity during the minimum is sporadic or regular by analyzing the distribution of days with registered sunspots.

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2. Phase evolution of sunspot activity cycles around the Maunder minimum

Since SA depicts the roughly 11-year quasi-cyclicity outside MM, we can apply the delayed component method to analyze this cyclicity. The method allows one to reconstruct, from a single time series, a multi-dimensional trajectory which is topologically similar to the actual trajectory of the system in an n-dimensional phase space (Takens 1981). Recently, the method has successfully been applied in the analysis of Wolf numbers (Kurths & Ruzmaikin 1990) and cosmic ray intensity variations during the last four solar cycles (Usoskin et al. 1997, 1998). A description of the method and related references are given, e.g., in (Usoskin et al. 1998). We used here the time delay of τ=30 months which is close to the first zero of the autocorrelation function, as discussed earlier (Usoskin et al. 1998). Since the 11-year cycle is quite stable everywhere outside the deep MM, the same delay τ applies for the time before and after MM.

The delayed component method requires the analysed series to be equispaced. However, some gaps exist even in the monthly averaged GSN data. We have filled the data gaps using a binomial interpolation within a 41-month time window. Thereafter, the monthly data series was smoothed with a 31-month running filter, similarly to (Usoskin et al. 1997, 1998). The final smoothed data series to be used in the delayed component analysis is shown in Fig. 1. The longest data gap of 27 months in the original monthly GSN data is in late 1740s, i.e., at the end of the period included in this study. Therefore, the data gaps are not expected to seriously affect the analysis around MM. Moreover, we have tested the chosen interpolation technique with an artificial series (noised 11-year sinusoid with gaps), finding that the

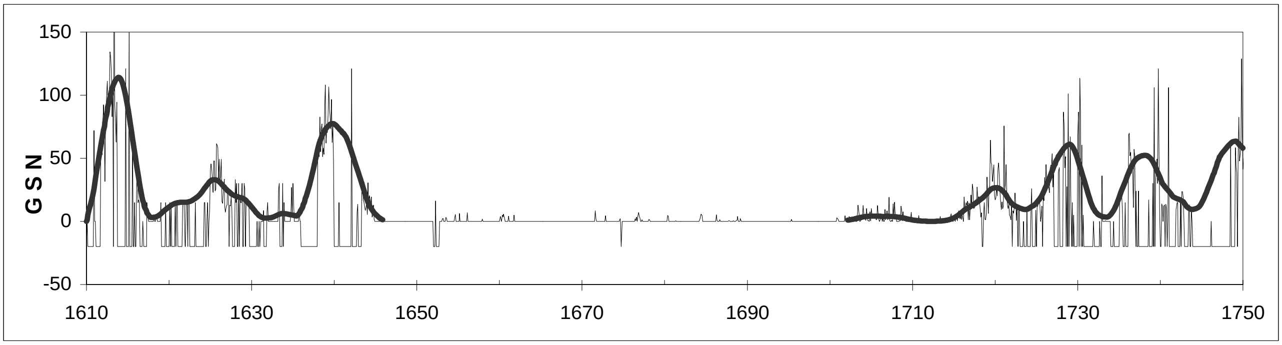

Fig. 1. Monthly raw and smoothed group sunspot numbers. Negative values are used to denote observational gaps.

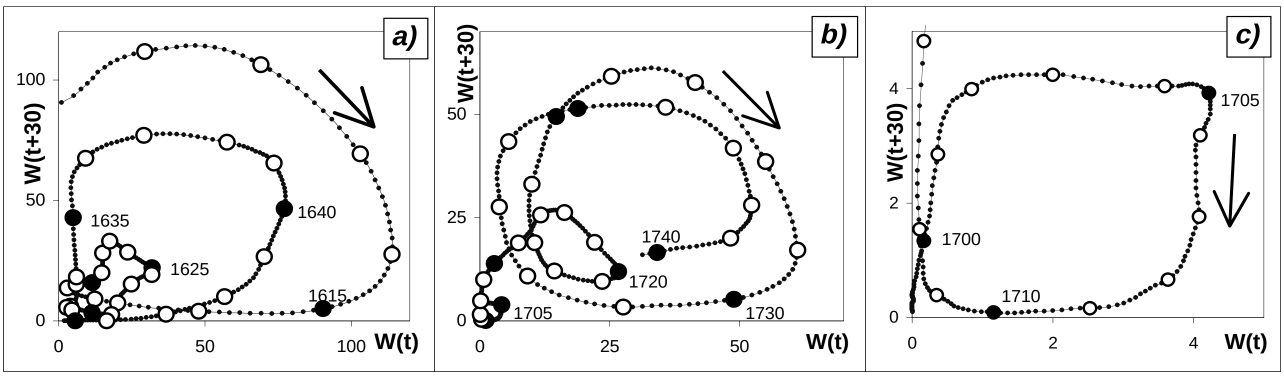

Fig. 2a – c. SA evolution, circles denote the start of each year. (Every fifth year is denoted by a black circle). Arrows shows the clockwise direction of evolution. **a** SA evolution in 1610-1645 before the Maunder minimum; **b** SA evolution in 1700-1740 after the deep Maunder minimum; **c** SA evolution during the exceptionally small cycle in 1700-1712.

data gaps were interpolated with an accuracy better than 10% for gaps shorter than 36 months.

The two-dimensional (2D) evolution of SA is shown in Fig. 2 for a few cycles before and after MM and for the extremely weak cycle within the minimum separately. The sunspot observations (GSN data) started in 1610 in the ascending phase of a big solar cycle (cycle BM-3, the third cycle before MM) whose phase space evolution was very regular, as shown by a large, fairly cyclic curve in Fig. 2a. The following cycle (BM-2) in 1618-1633 was much weaker and depicted a rather irregular phase pattern (see Fig. 2a). This irregularity probably reflects the rather poor observations with several years of equal monthly GSN values in the beginning of this cycle. Therefore, we regard the phase pattern of this cycle as rather uncertain. However, its rather small amplitude is beyond doubt. The last cycle before the minimum (BM-1) in 1633-1645 evolved regularly until about 1642-1643 when it started decreasing very rapidly to zero. Accordingly, the phase behaviour of the cycles prior to MM (at least BM-3 and BM-1) was quite similar to that of the recent cycles 19-22 (Usoskin et al. 1997).

The phase evolution of SA at the end and after MM was rather different (see Figs. 2b and 2c). The small cycle in 1700-1712 (cycle -4 according to the common cycle numbering; see Fig. 2c) was very regular and its phase space evolution (distribution of points along the curve) was quite uniform despite its unprecedentedly low amplitude. (The amplitude maximum in 1705 corresponds to the minima of recent cycles). Somewhat later, soon after 1720, the phase evolution became regular again. However, between cycle -4 and the final recovery of the normal cyclic behaviour, i.e., roughly in 1712-1720, a transition period took place. This period was not cyclic but was manifested as a slow rise of the overall SA level (see Figs. 1 and 2b). This period depicts a phase catastrophe when the regular phase evolution of the solar cycle was disturbed.

3. Sunspot activity in the Maunder minimum

Fortunately, MM was very well covered with sunspot observations (Hoyt & Schatten 1996). As discussed above, SA was fairly regular already before the end of MM, since about 1700. However, sunspots appeared only rarely and seemingly sporadically during the deep minimum of approximately 1645-1700. During this period, sunspots were observed in less than 2% of observed days. (On the other hand, the coverage of daily observations was more than 95%). Because of the sparse appearance of sunspots with very low values, traditional methods of time series analysis are not appropriate for this period. This applies, e.g., to the wavelet method used by Frick et al.(1997).

To overcome this problem, we have used a new approach. Note first that the exact number of sunspots observed on a single day of the deep MM is not very reliable since the number of observers (with imprecise instrumentation) was small. Moreover, the daily numbers were consistently very small and their uncertainties large (Hoyt & Schatten 1996, 1998). In order to reduce this "noise" we deal with the number of days with observed sunspots rather than with the GSN numbers themselves. Accordingly, in order to analyze SA during the deep minimum (1645-1700), we constructed from the original series of daily GSN values 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 (see Fig. 3a). Then we studied the concentration (or frequency) of sunspot appearance using the following technique. (A similar method was recently used in the analysis of solar γ-rays by Efremova et al. 1997). Starting from day T_o, one can count the number of days with sunspots $N = \sum S(t)$ until $N = N_o$ at time T_1 (N_o being fixed). One can then obtain the average concentration of days with sunspot groups within the interval $[T_o, T_1]$:

$$P = N_o/(T_1 - T_o + 1) \quad (1)$$

This value P is associated with the following average date ("mass center") of days with sunspots within the time interval in question:

$$T_c = \frac{1}{N_o} \sum_{j=1}^{N_o} t_j, \quad (2)$$

where t_j are days with sunspots within the interval. Then one slides the starting time T_o and repeats the calculation. The ensuing concentration of sunspot occurrence is shown in Figs. 3b and 3c for N_o=30 and N_o=50, respectively.

One can see from Fig. 3 that the sunspot occurrence can be grouped into two fairly long intervals, 1652-1662 and 1672-1689. No sunspots were reported outside these intervals except for few days in 1695 due to one sunspot group. We have estimated the probability of the long intervals without sunspots to be due to random fluctuations. This probability is $3 \cdot 10^{-5}$ and $6 \cdot 10^{-7}$ for the intervals 1645-1651 and 1662-1671, respectively. The corresponding probability to find one sunspot group in 1689-1700 is about 10^{-5}. On the other hand, the probability of a random occurrence of 147 days with sunspots during the period 1652-1661 is $2 \cdot 10^{-4}$ and the corresponding probability of 209 sunspot days in 1671-1689 is $5 \cdot 10^{-3}$. These estimates are completely independent of the sunspot occurrence analysis method discussed above, and strongly support the idea of SA being grouped into two separate intervals with no activity inbetween.

The mass centers for these two intervals calculated from an equation similar to Eq. (2) are found at about 1658 and 1679/1680, respectively. (They are noted by the two long arrows in Fig. 3c). Because of rather poor data coverage in 1652 and 1674, the results for these years are somewhat uncertain. However, since both of these years are within either of the two main groups mentioned above, this uncertainty does not affect the main result. We also note that taking into account the actual daily GSN values as weighting factors in Eq. (2) would only slightly affect our results, changing the positions of the mass centers by a couple of months. Together with the maximum of cycle BM-1 in 1639/1640 and the maximum of cycle -4 in 1705, the two sunspot occurrence concentrations during MM strongly indicate that the dominant remaining periodicity in SA during this time is the 22-year cycle.

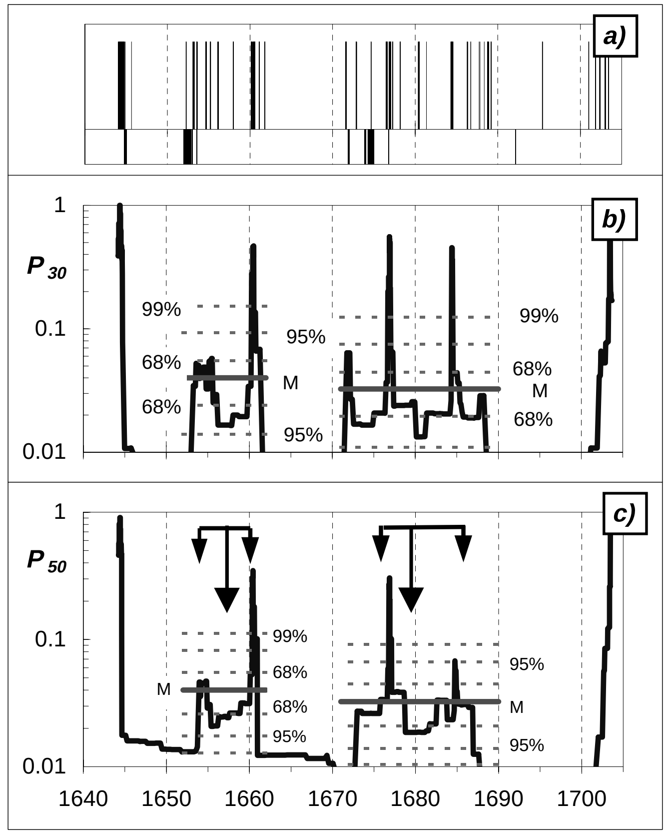

Fig. 3a – c. Days with sunspot activity during the Maunder minimum. **a** Positive bars denote days with observed sunspots, zero means days with no sunspots observed and negative bars denote days with missing observations; **b** Concentration of days with reported sunspots for $N_o = 30$, mean value (M) and significance levels are shown with solid and dashed lines, respectively; **c** The same as b) but for $N_o = 50$; long (short) arrows denote the mass centers of the two main groups (two subgroups) of days with sunspots.

In addition to this main division of GSN days into two intervals, there may also be some substructure within the two groups. With some caveat, this analysis suggests that each of the two main intervals can be split into two sub-intervals as follows (see Fig. 3):

[1652-1662] $\longrightarrow$ [1652-1657] and [1659-1662]
[1672-1689] $\longrightarrow$ [1672-1681] and [1682-1689]

The mass centers of these sub-intervals are noted by the short arrows in Fig. 3c. Note that the two peaks of the second group are separated by roughly 10 years which, together with a few days with observed sunspots in 1695, might be an indicator of a weak (relative to the dominant 22-year cycle) Schwabe cycle in the second half of MM (cf Ribes & Nesme-Ribes 1993). On the other hand, the peaks of the first group are too close to support the existence of 11-year cyclicity in the first half of MM. We have studied the significance of these peaks and calculated the 68%, 95% and 99% confidence levels against the zero hypothesis of sporadic sunspot occurrence. These levels are shown in Fig. 3 together with the mean values. We find that two peaks (in 1660 and 1677) are highly significant and very stable against varying N_o, while others are less reliable. Accordingly, the sub-division of SA within the two main intervals, and thereby the Schwabe cycle, is less founded statistically than the main grouping.

4. Discussion

The above results can be summarized to the following scenario for SA in and around the Maunder minimum. Before MM the SA evolution was fairly regular (similar to nowadays), depicting a dominant 11-year cyclicity. In the early 1640s SA abruptly lost the 11-year cyclic behaviour and fell into the great minimum. During the deep minimum (1645-1700) the Schwabe cyclicity was greatly suppressed (at least during the first half of MM), but a 22-year cycle existed in the seemingly sporadic occurrence of sunspots with maximum concentrations around 1658 and 1680. Towards the end of MM the Schwabe cyclicity was recovering and an exceptionally weak but very regular Schwabe cycle appeared in 1700-1712 (cycle -4), marking the end of the deep minimum. We note that although cycle -4 was very regular, it is still part of MM since, firstly, the activity was due to the increased number of days with sunspots rather than due to large GSN values and, secondly, the north-south asymmetry of sunspot distribution, typical for the deep MM, was still very strong during this cycle (Sokoloff & Nesme-Ribes 1994). After cycle -4, a transition period in 1712-1720 with the implied phase catastrophe raised SA from the weak level of the minimum to a more normal level with a regular 11-year cyclicity.

The weakness of the Schwabe cycle during MM implies a suppression of the regular dynamo process in that period. The seemingly sporadic occurrence of sunspots during MM can be associated with a randomly fluctuating magnetic field in the convection zone (Ruzmaikin 1997 and references therein). On the other hand, the remaining 22-year cyclicity suggests for a 22-year modulation of the fluctuating field. Such a modulation may exist even with a regular dynamo but is masked by the high sunspot activity. We note that the known Gnevyshev-Ohl rule (e.g. Gnevyshev & Ohl 1948; Wilson 1988; Storini & Sykora 1997) is valid at least after the Dalton minimum in early 1800's. According to this rule, the sum of sunspot numbers for an odd-numbered cycle exceeds that of the preceding even-numbered cycle. The Gnevyshev-Ohl rule suggests for a weak 22-year cycle superimposed on the Schwabe cycle. Note also that the small amplitude of cycle BM-2 supports the validity of the Gnevyshev-Ohl rule even prior to MM, and the idea that the decrease of the Schwabe cycle with respect to the 22-year cycle started already slightly before MM. Although the Gnevyshev-Ohl rule is only relatively weakly visible during the high-amplitude recent cycles, it may show up much more clearly during the suppressed activity of great minima. Note that such a behaviour is expected if a weak relic magnetic field exists in the Sun since it should result in a 22-year modulation of SA (e.g. Sonett 1983; Levy & Boyer 1982; Boruta 1996).

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