THE START OF THE DALTON MINIMUM: WAS ONE SUNSPOT CYCLE LOST IN LATE XVIII CENTURY?

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ABSTRACT

We have recently suggested that one solar cycle was lost in the beginning of the Dalton minimum because of sparse and partly unreliable sunspot observations during 1790s (Usoskin et al. 2001). So far this cycle has been combined with the preceding activity to form the exceptionally long solar cycle #4 in 1784-1799 which has an irregular phase evolution (known as the phase catastrophe) and other problems discussed in earlier literature. Based on a re-analysis of available sunspot data, we have suggested that solar cycle #4 is in fact a superposition of two cycles: a normal cycle in 1784-1793 ending at the start of the Dalton minimum, and a new weak cycle in 1793-1800 which was the first cycle within the Dalton minimum. Including the new cycle resolves the phase catastrophe and leads to a consistent view of sunspot activity around the Dalton minimum. It also restores the Gnevyshev-Ohl rule of cycle pairing across the Daltom nimimum. Here we summarize these findings and show that the existence of a new cycle is supported by the auroral occurrence in Europe in late XVIII century.

1. INTRODUCTION

Sunspot numbers form the longest directly observed index of solar activity (SA). The well known Wolf sunspot number (WSN) series has been used as a measure of sunspot activity for more than a century. Recently, a new, greatly improved and more homogeneous group sunspot number (GSN) series was introduced (Hoyt & Schatten 1998) which includes many additional early observations and covers the period since 1610. The new GSN series has been shown to be more correct than WSN for the period before 1850 (Hoyt & Schatten 1998; Letfus 1999).

Some exceptional periods exist in the time series of sunspot observations. One such period is the Dalton

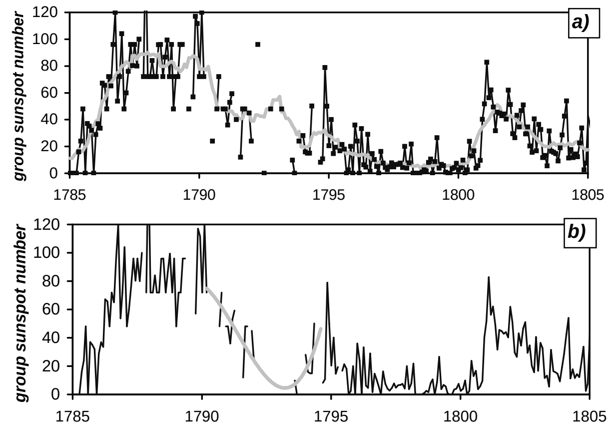


Figure 1. Monthly group sunspot numbers. The lines join the neighboring monthly values if existent. a) All available monthly data. The thick grey line is the 13-month running average. b) Only connected monthly data. The thick grey line is the best-fitting third order polynomial.

minimum (DM) at the turn of 18^{th} and 19^{th} century. The years 1790-1794 at the beginning of DM were very poorly covered by sunspot observations (Fig. 1a), probably because of the unstable political situation in Europe after the French revolution in 1789. E.g., Sonett (1983) suspected that there was an error in the WSN series in 1780-1800. Wilson (1988) noted on a probable misplacement of sunspot minima for cycles 4, 5 and/or 6. The cyclic evolution of SA is distorted during the exceptionally long declining phase of cycle #4 in 1791-1798, leading to the suggested phase catastroph (e.g., (Kremliovsky 1994)), when the phase evolution of SA was rather linear than cyclic. Note that these results were obtained from the WSN series which was constructed by interpolating (without explicit notice) over sparse points, leading to large systematic errors of up to 50 in WSN for the last decades of 18^{th} century (Hoyt & Schatten 1998; Letfus 1999). Using the GSN series and analyzing the original (not interpolated or pre-processed) data by individual ob-

Table 1. Best fitting parameters and correlation coefficients of Fig. 3.

period	m	b	R
after DM	0.92±0.14	1850±850	0.935
standard cycle numbering			
before DM	0.16±0.23	2380±1110	0.322
entire	0.76±0.25	1485±1380	0.66
new cycle numbering			
before DM	1.14±0.14	900±460	0.969
entire	1.00±0.08	1370±400	0.963

servers, we have recently suggested that one weak solar cycle was probably lost at the beginning of DM (Usoskin et al. 2001). We analyze here the available data and suggest for a consistent solution to the above questions and problems.

2. 22-YEAR CYCLICITY IN SUNSPOT ACTIVITY

The well-known Gnevyshev-Ohl (GO) rule (e.g., (Gnevyshev & Ohl 1948; Wilson 1988)) orders sunspot cycles to even-odd pairs so that the intensity I (sum of monthly sunspot numbers over the cycle) of the odd cycle is larger than that of the preceeding even cycle. Fig. 2a illustrates the GO rule for the GSN series. Note that the GO rule is valid in this form since cycle pair 6-7 but not for the period before DM. According to the GO rule, the two cycles within the even-odd pair are highly correlated while the correlation is poor in the reversed order. Fig. 3a illustrates the cycle pairing according to the GO rule. In Table 1 we show the coefficients of the linear fitting

$$I_{2k+1} = m \cdot I_{2k} + b, \qquad (1)$$

and the correlation coefficient R as quantitative measures for cycle pairing. As seen in Table 1 and Figs. 2a and 3a, the cycles do not follow the GO rule before DM when using the standard cycle numbering. However, as we have recently shown (Mursula et al. 2001), the GO rule is valid even before DM in a phase-reversed form, where the even cycle is coupled with the preceding odd cycle. Moreover, a persistent 22-year cyclicity exists in sunspot intensity which did not suffer a significant phase change across DM (Mursula et al. 2001). Accordingly, all sunspot cycles should be ordered according to Eq. 1 with $m = 1$ and $b \approx 1500$ as approximately found for the time after DM (see row 1 in Table 1). Note that the observed 22-year cyclicity resulted from a continuous analysis of the GSN time series which is independent of cycle definition. Therefore, the fact that the phase reversal exists in the GO rule but not in the continuous 22-year cyclicity, leads to the conclusion that cycle numbering was out of phase before and after DM.

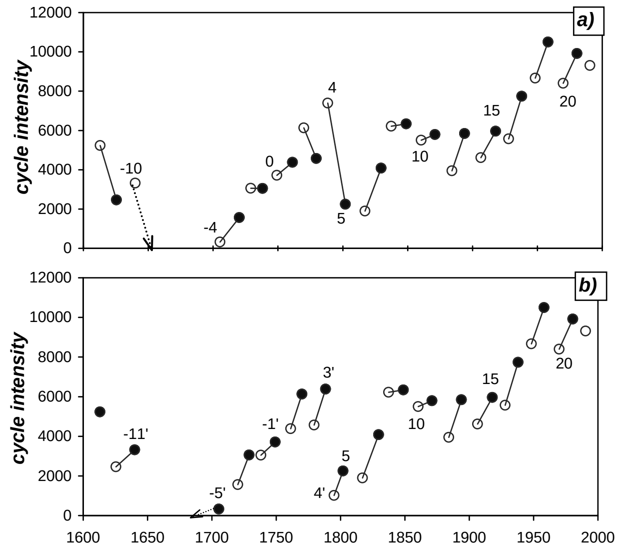


Figure 2. Intensities (sum of sunspot numbers) of sunspot cycles in pairs of even (open circles) and odd (filled circles) cycles. a) Standard cycle numbering; b) Numbering after including the new cycle #4'.

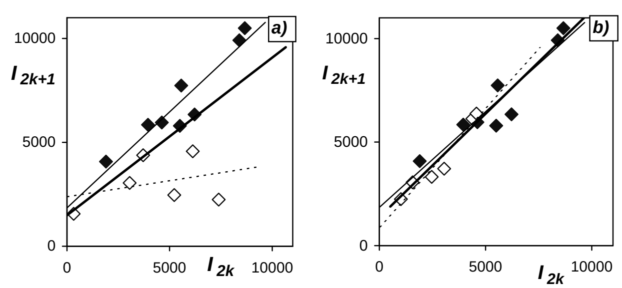
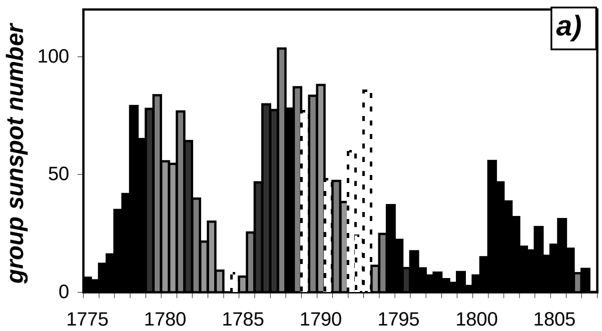


Figure 3. Intensities of odd sunspot cycles vs. even cycles for a) standard cycle numbering; b) numbering suggested in the paper. Open (filled) diamonds correspond to the interval before (after) DM. Dotted, thin and thick solid lines give the linear fit (Eq. 1) before and after DM, and for the entire period, respectively. Best fitting parameters are given in Table 1.



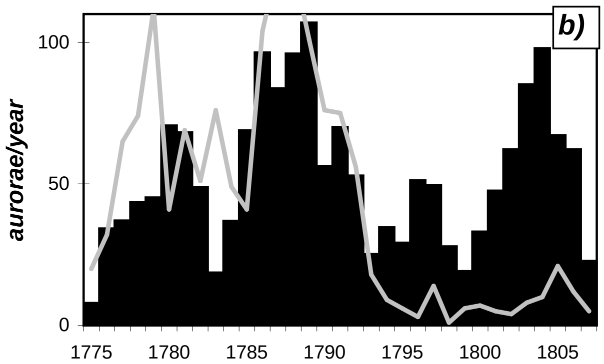


Figure 4. a) Semiannual GSN data at the beginning of DM. White, light grey, dark grey and black shadings denote unreliable (< 6 observation days during the corresponding 6 months), poorly reliable (6-12 days), reliable (13-24 days), and highly reliable (> 24 days) values. b) Yearly number of aurorae in Sweden (Silverman 1983) and in Central Europe (Křivský & Pejml 1988) are presented by bars and grey curve, respectively.

3. LOST CYCLE

As noted above, the period at the start of the Dalton minimum was poorly covered by sunspot observations (Fig. 1). E.g., there were only 4 days when sunspot observations were made during the year 1792. Also, the accuracy of daily sunspot numbers was rather poor during that period. Since traditional methods of time series analysis are not appropriate for that period, we performed recently a detailed analysis of daily observations taking into account the reliability of each individual observer for 1790s (Usoskin et al. 2001). The semiannual GSN values with estimate of their reliability are shown in Fig. 4 for the period under investigation. One can see that sunspot numbers were unreliable in 1789, 1790, 1792, and 1793, while they were reliable since 1795 and more or less reliable in the ascending phase in 1786-88 (see also Hoyt & Schatten 1998). Years 1792 and 1793 are particularly questionable since the indicated high SA during these years is based on very few observations. In (Usoskin et al. 2001) we suggested that, because of the sparse and unreliable sunspot observations, one weak cycle was completely lost at the beginning of DM, and the exceptionally long SA cycle #4 in fact consisted of two cycles, one in 1784-1793 and the other in 1793-1800. In order

Table 2. Minimum and maximum times of sunspot cycles around the Dalton minimum.

Standard numbering			New numbering		
#	min	max	#	min	max
4	1784.3	1788.4	3'	1784.3	1788.4
			4'	1793.1*	1795*
5	1798.7	1802	5	1799.8*	1802.5*
6	1810.8	1817.1	6	1810.8	1817.1
7	1823	1829.6	7	1823	1829.6

* suggested estimate

to illustrate the situation in the beginning of DM we discarded the isolated monthly GSN values (isolated points in Fig. 1a). The more consistent the sunspot observations were, lasting over several subsequent months, the more reliable the corresponding monthly GSN values are. When applied to the critical years 1792-1793, this rule neglects all other monthly values except for August and September 1793 when most observations from these years have been made. Moreover, these two months contain the only observations during these years that were considered reliable according to (Hoyt & Schatten 1998). Accordingly, this simple rule excludes all unreliable monthly GSN values. We have depicted only these reliable "connected" GSN monthly values in Fig. 1b. As seen there, the data clearly suggest for an additional minimum of SA in 1793. We have fitted the GSN values of Fig. 1b for 1790-1795 by a polynomial of third degree, finding the additional minimum in 1793.1. According to this result, the cycle starting in 1784 is now cycle #3' and ends in 1793. It was evolving regularly until declining rather rapidly to a minimum in 1793, followed by the new weak cycle, now numbered as cycle #4', denoting the start of the Dalton minimum. Note that this behaviour closely resembles the evolution of the last solar cycle before the Maunder minimum (Usoskin et al. 2000). Table 2 shows the minimum and maximum times of the solar cycles around DM using the standard and new cycle numbering.

With the new cycle, the GO rule is valid in its original form (Gnevyshev & Ohl 1948) without exceptions throughout the entire SA interval of about 400 years (Fig. 2b). Moreover, the intensity differences between the odd and even cycles of a pair are now roughly equal. Therefore, the correlation between the odd and even cycle of a GO pair becomes very strong and persistent throughout the entire period (see Fig. 3b and Table 1), as expected from the persistent 22-year periodicity in SA (see Section 2 and (Mursula et al. 2001)). In particular, this correlation before DM is significantly improved with the new numbering, which also improves the overall correlation. With the introduction of the new cycle, the phase catastrophe (Kremliovsky 1994), associated with the prolonged descending phase of cycle 4, disappears. Instead, the phase evolution of all cycles is quite regular. Therefore, the new cycle suggested by Usoskin et al. (2001a), resolves the problems of

SA evolution around the Dalton minimum.

4. AURORAL OBSERVATIONS

Strictly taken, only new, more reliable sunspot observations, or the latitudinal distribution of sunspots and the reconstruction of the Maunder butterfly diagram in 1790s could give a solid proof for the existence of the lost cycle. Unfortunately, such information is not known to exist (Usoskin et al. 2001). However, other heliospheric parameters dependent on solar activity may yield some less direct evidence in favor of the new cycle.

Visual auroral observations are commonly used as an indirect proxy of SA for early times (see, e.g., Silverman 1992). Auroral observations from two data sets are shown in Fig. 4b for the period studied. Black bars depict the annual series of visual aurorae in Sweden (latitude about 60^o) according to the Rubenson catalogue (Silverman 1983). Grey line depicts the annual series of aurorae observed at middle latitudes ($< 55^o$) in central Europe (Křivský & Pejml 1988). Note first the difference in overall activity level between the two auroral data sets. While the high-latitude auroral activity (Silverman 1983) roughly retains its level even within the Dalton minimum, the mid-latitude activity (Křivský & Pejml 1988) is greatly reduced during DM. This is understandable since the high-latitude auroral activity better responses to small solar disturbances while the occurrence of mid-latitude auroras requires large storms. However, both auroral data sets depict a significant and concurrent decrease of auroral activity at the start of the Dalton minimum. Such a dramatic decrease can not be understood if the solar activity was as high as given by the official Wolf sunspot numbers. On the other hand, this decrease corresponds very well with the suggested additional SA minimum in 1793.

Despite the difference in the overall activity level, the two auroral data sets depict quite a similar detailed structure over the time interval depicted in Fig. 4. In particular, both data sets have a clear, separate maximum in the declining phase of the new cycle #4' in 1796-97. This gives new, independent evidence in favor of the lost cycle. Although the maximum at mid-latitudes is quite small, it is interesting to note that it is not much smaller than the corresponding maximum during the next, well-established cycle #5. This shows that large geomagnetic storms were quite rare during the whole Dalton minimum. Note also that the auroral maximum of cycle #4' occurs 1-2 years after the sunspot maximum which is typical for present cycles. However, if this maximum would be part of the exceptionally long cycle #4, it would be abnormally detached and far from the earlier part of the cycle, abnormally large (especially according to the high-latitude auroral series) and abnormally close to the subsequent sunspot minimum.

5. SUMMARY

1. Based on a re-analysis of sunspot observations we have suggested that one solar cycle was lost in 1790s (Usoskin et al. 2001). This cycle, numbered as #4', started in 1793, reached its maximum in 1795 and ended in 1799-1800.
2. The new cycle restores the Gnevyshev-Ohl rule across the Dalton minimum making it valid throughout the entire 400 years of sunspot observations. The new cycle also resolves the problem of phase catastrophe around the turn of XVIII-XIX centuries, leading to a consistent view of solar activity.
3. The new cycle leads to a similar behaviour of sunspot activity around the Dalton and Maunder minima: an abrupt decline of a normal cycle followed by a gradual restoration of activity.
4. We have shown that there is new strong evidence for the existence of the new cycle from two independent series of visual observations of aurorae in Europe.

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