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Was one sunspot cycle lost in late XVIII century?

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Abstract. We suggest that one solar cycle was lost in the beginning of the Dalton minimum because of sparse and partly unreliable sunspot observations. So far this cycle was combined with the preceding activity to form the exceptionally long solar cycle #4 in 1784-1799, leading to an irregular phase evolution of sunspot activity (known as a phase catastrophe) and other problems. We reanalyze the available group sunspot numbers and suggest that solar cycle #4 was 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 full cycle within the Dalton minimum. Including the new cycle resolves the problems mentioned above and leads to a consistent view of sunspot activity around the Dalton minimum. Moreover, it will restore the Gnevyshev-Ohl rule of cycle pairing throughout the 400-year interval of sunspot observations.

Key words. Sun: activity – Sun: sunspots – Sun: Dalton minimum – Sun: solar cycle

1. Introduction

Sunspot numbers form the longest directly observed index of solar activity (SA). The well known Wolf sunspot number (WSN) series, R_z, (e.g., Waldmeier 1960) 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, R_g, 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 are included in the time interval of sunspot observations. One such period is the Dalton minimum (DM) at the turn of 18th and 19th 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, mentioning that "clearly, something is amiss in Hale cycle 3". The evolution of SA is distorted during the exceptionally

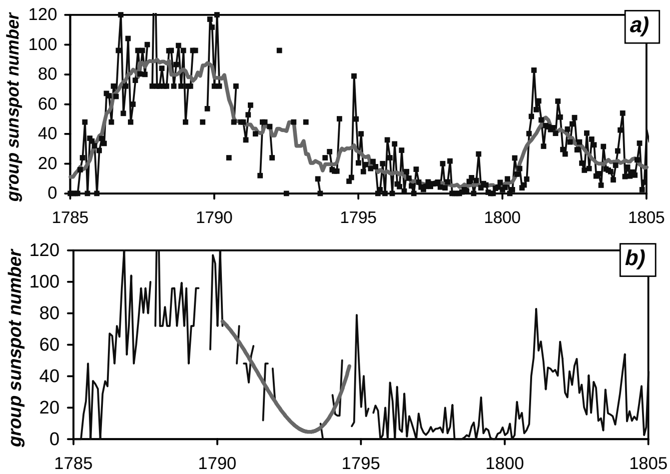

Fig. 1. Monthly group sunspot numbers. The lines join the neighboring monthly values if existent. **a)** All available monthly data. The thick grey line is the 13-month running average. **b)** Only connected monthly data. The thick grey line is the best-fitting third order polynomial

long declining phase of cycle #4 in 1791-1798, leading to the suggested phase catastroph (e.g., Vitinsky et al. 1986; Kremliovsky 1994), when the phase evolution of SA was not cyclic but linear. Note that these results were obtained from the WSN series which was constructed by interpolating (without explicit notice) over sparse points,

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leading to large systematic errors of up to 50 in R_z units for the last decades of 18th century (Hoyt & Schatten 1998; Letfus 1999). Since the GSN series is based on a larger observational data set and allows to study the original (not interpolated or pre-processed) data by individual observers, we use the GSN series to reanalyze solar activity in the beginning of DM. We suggest for a consistent solution to the above questions and problems.

2. GO rule and 22-year cyclicity in sunspot activity

The well-known Gnevyshev-Ohl (GO) rule (e.g., Gnevyshev & Ohl 1948; Wilson 1988; Storini & Sykora 1997) orders sunspot cycles to even-odd pairs so that the intensity (sum of sunspot numbers over the cycle) of the odd cycle is larger than that of the preceeding even cycle. Figure 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. Gnevyshev & Ohl (Gnevyshev & Ohl 1948) and, later, Wilson (1988) showed that the two cycles within the even-odd pair are highly correlated while the correlation is poor in the reversed order. Figure 3a illustrates the cycle pairing according to the GO rule. In Table 1 we show the coefficients of the linear fitting

$$I_{2k+1} = m \cdot I_{2k} + b, \tag{1}$$

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 shown recently (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. We also gave evidence for a persistent 22-year cyclicity in sunspot intensity which was interpreted in terms of a relic field in the Sun (Mursula et al. 2001). According to these results, 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). Most importantly, Mursula et al. (2001) found out that, although the GO rule requires a phase reversal across DM, the 22-year cyclicity in SA did not suffer a significant phase change around DM. 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 (see also Sonett 1983).

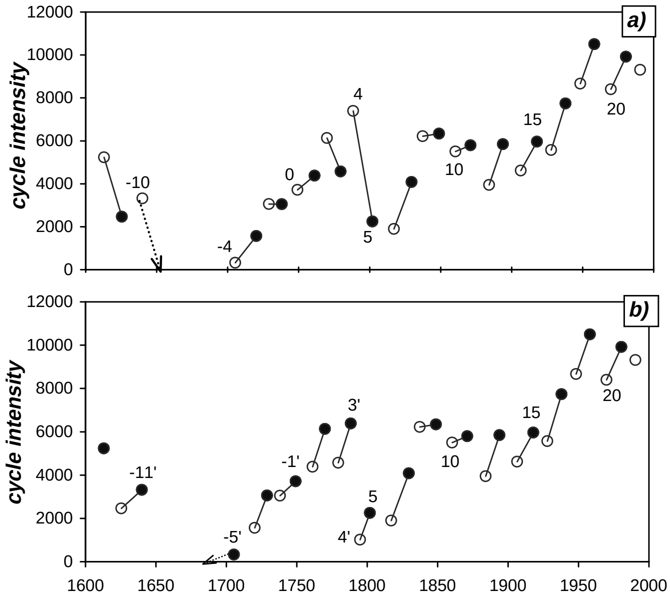

Fig. 2. Intensities of sunspot cycles in pairs of even (open circles) and odd (filled circles) cycles. **a)** Standard cycle numbering; **b)** Numbering after including the new cycle #4′

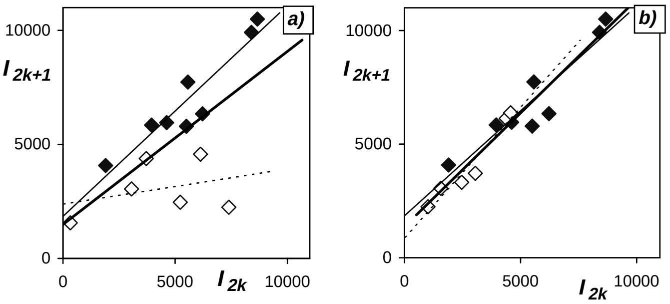

Fig. 3. Intensities of odd sunspot cycles vs. even cycles for **a)** standard cycle numbering; **b)** numbering suggested in the paper. Open (filled) diamonds correspond to the interval before (after) DM. Dotted, thin and thick solid lines give the linear fit (Eq. (1)) before and after DM, and for the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

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

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

3. Beginning of the Dalton minimum

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. E.g., the day of 3 April 1791 was observed by 6 different observers in Europe, and the reported sunspot group numbers for that day varied from 1 to 6 (Hoyt & Schatten 1998). It has been estimated that the annual GSN value is unreliable if obtained using less than 20 daily observations, more or less evenly distributed over the year (Hoyt & Schatten 1998). As a compromise

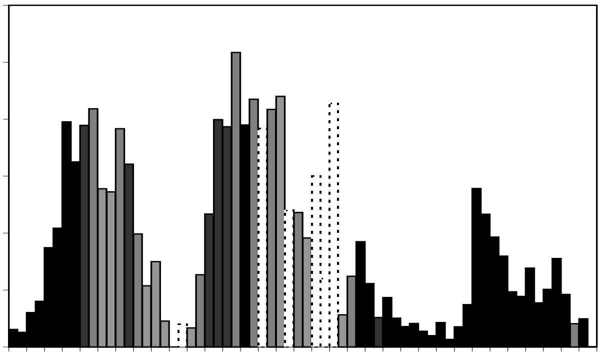

Fig. 4. Semiannual GSN data at the beginning of DM. White, light grey, dark grey and black shadings denote unreliable (<6 observation days during the corresponding 6 months), poorly reliable (6–12 days), reliable (13–24 days), and highly reliable (>24 days) values

between time resolution and statistics, we depict the semiannual GSN values in Fig. 4. Shading of the bars in Fig. 4 represents the number of sunspot observation days during the 6-month interval and, thus, reflects the reliability of the corresponding semiannual GSN value. 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 the following we will analyze the daily sunspot group observations during these years.

The daily group sunspot number is calculated as

$$R_{\rm g} = \frac{12.08}{N} \sum_i k_i G_i \qquad (2)$$

where G_i is the number of sunspot groups reported by ith observer, k_i is the observer's correction factor, N is the number of observers for that day, and 12.08 is the normalisation factor scaling $R_{\rm g}$ to $R_{\rm z}$ (Hoyt & Schatten 1998). In Table 2 we show all the available sunspot observations for 1792-1793 included in the GSN series. We note that only isolated observations existed in 1792-1793.5 separated by more than two months. Also, the high $R_{\rm g}$ value for the first half of 1793 is mainly based on the observation by Huber of 4 sunspot groups on 28 May 1793. Since the individual correction factor for Huber is very high ($k = 2.564$), the corresponding daily $R_{\rm g}$ is as high as 123. On the other hand, Hoyt & Schatten (1998) regard observers with $k > 1.4$ and $k < 0.6$ as poor observers whose observations should be discarded if possible. Thus, the monthly GSN numbers during 1792-1793.5 are based on very sparse daily observations and therefore one can expect very large systematic errors during this period. Note that all observations listed in Table 2 were used in WSN series.

Table 2. Daily sunspot group observations in 1792 and 1793 (Hoyt & Schatten 1998)

date (y.m.d)	G	observer, place	k	$R_{\rm g}$
1792.01.20	1	Staudacher, Nürnberg	2.0	24
1792.04.28	4	Staudacher, Nürnberg	2.0	96
1792.07.23	0	Staudacher, Nürnberg	2.0	0
1792.10.21	2	Staudacher, Nürnberg	2.0	48
1793.03.09	2	Staudacher, Nürnberg	2.0	48
1793.05.28	4	Huber, Basel	2.564	123
1793.08.05	1	Staudacher, Nürnberg	2.0	24
1793.08.29	1	Staudacher, Nürnberg	2.0	24
1793.08.30	0	Staudacher, Nürnberg	2.0	0
1793.08.31	0	Staudacher, Nürnberg	2.0	0
1793.09.01	0	Staudacher, Nürnberg	2.0	0
1793.09.02	0	Staudacher, Nürnberg	2.0	0
1793.09.03	0	Staudacher, Nürnberg	2.0	0
1793.09.04	0	Staudacher, Nürnberg	2.0	0
1793.09.04	0	Schroter, Lilienthal	1.255	0
1793.09.04	0	Bode, Berlin	0.993	0
1793.09.05	0	Staudacher, Nürnberg	2.0	0
1793.09.05	1	Schroter, Lilienthal	1.255	15
1793.09.05	0	Bode, Berlin	0.993	0
1793.11.03	1	Staudacher, Nürnberg	2.0	24

4. The lost cycle

Here we discuss the possibility that, because of the sparse and unreliable sunspot observations, one weak cycle was completely lost at the beginning of DM. We suggest that the exceptionally long SA cycle #4 in fact consisted of two cycles, one in 1784-1793 and the other in 1793-1800. This suggestion is based on the idea that, because of the above discussed problems in sunspot observations, one minimum of sunspot activity remained unnoticed. In order to estimate the more correct time profile of SA evolution 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. As seen in Table 2, most observations from these years have been made during these two months. Moreover, these two months contain the only observations during these years that were considered reliable ($0.6 < k < 1.4$) by Hoyt & Schatten (1998). Accordingly, this simple rule excludes all unreliable monthly GSN values for these two years. We have depicted the "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 connected 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, denoting the start of the Dalton minimum. Note that this behaviour closely resembles the evolution of the last solar

Table 3. Minimum, maximum and median times of sunspot cycles around the Dalton minimum

Standard numbering				New numbering			
#	min	max	med	#	min	max	med
4	1784.3	1788.4	1789.5	3′	1784.3	1788.4	1788.5*
				4′	1793.1*	1795*	1795.2*
5	1798.7	1802	1802.9	5	1799.8*	1802.5*	1803.1*
6	1810.8	1817.1	1817.2	6	1810.8	1817.1	1817.2
7	1823	1829.6	1829.3	7	1823	1829.6	1829.3

* Suggested estimate.

cycle before the Maunder minimum (Usoskin et al. 2000). However, while the 11-year cyclicity (nearly) vanished in the early part of the Maunder minimum, it seems to have prevailed during DM, starting with the new weak cycle, now numbered as cycle #4′. Table 3 shows the minimum, maximum and median times (Mursula & Ulich 1998) of the solar cycles around DM using the standard and new cycle numbering.

With the new cycle, the GO cycle pairing and ordering 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 Sect. 2 and Mursula et al. 2001). In particular, this correlation before DM is significantly improved with the new numbering, which also improve the overall correlation. With the introduction of the new cycle, the phase catastrophe (Vitinsky et al. 1986; Kremliovsky 1994), associated with the prolonged descending phase of cycle 4, disappears. Instead, the phase evolution of all cycles is quite regular.

5. Conclusions

In this paper we have suggested that one solar cycle was lost in 1790s because of sparse and partly unreliable sunspot observations. So far, this cycle has been combined with the preceding activity to form an exceptionally long cycle #4, resulting in a phase catastrophe and other problems in SA evolution (e.g., Sonett 1983; Vitinsky et al. 1986; Wilson 1988; Kremliovsky 1994; Mursula et al. 2001). The lost cycle #4′ was weak, starting the Dalton minimum in 1793 (see Fig. 1b and Table 3). With the new cycle, the cycle numbering before DM is changed and odd cycles are changed to even cycles and vice versa. We have shown that, with the new cycle and the implied new numbering, all the above mentioned problems disappear, leading to a consistent view of solar activity. In particular, the problem of the phase catastrophe and the reversal of the Gnevyshev-Ohl rule at the turn of 18^{th} and 19^{th} centuries are resolved. Moreover, new cycle leads to a similar behaviour of sunspot activity around the Dalton minimum as around the Maunder minimum (Usoskin et al. 2000): an abrupt decline of a normal cycle followed by a gradual restoration of activity.

Finally, we would like to note that only the latitudinal distribution of sunspots and the reconstruction of the Maunder butterfly diagram could test and possibly prove the suggestion presented and motivated in this paper. Unfortunately, such information is not known to exist (personal communications, see acknowledgements). Also note that indirect proxies (like auroras and cosmogenic isotopes) can not reliably reconstruct sunspot activity in 1792-1793 since they are not directly related to sunspot activity on such short time scales, especially during great minima of solar activity (Usoskin et al. 2001).

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