Lost sunspot cycle in the beginning of Dalton minimum: New evidence and consequences

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[1] We have recently suggested that one solar cycle was lost in the beginning of the Dalton minimum during 1790s [*Usoskin et al.*, 2001]. Earlier, this cycle has been combined with the preceding activity to form the exceptionally long solar cycle 4 in 1784-1799 with an irregular phase evolution. Here we show that historical data of auroral occurrence provide independent evidence for the existence of the new cycle. Using a heliospheric model we demonstrate that ^{10}Be or any other cosmogenic isotope data do not exclude the possibility of a new cycle. We also discuss the other implications of the new cycle for solar activity, in particular the cycle length distribution and the Waldmeier relation between the cycle amplitude and the length of the ascending and descending phase. Including the new cycle also restores the Gnevyshev-Ohl rule of cycle pairing and removes the phase catastrophe in the beginning of the Dalton minimum. *INDEX TERMS:* 7536 Solar Physics, Astrophysics, and Astronomy: Solar activity cycle (2162); 1650 Global Change: Solar variability; 2162 Interplanetary Physics: Solar cycle variations (7536). **Citation:** Usoskin, I. G., K. Mursula, and G. A. Kovaltsov, Lost sunspot cycle in the beginning of Dalton minimum: New evidence and consequences, *Geophys. Res. Lett.*, *29*(24), 2183, doi:10.1029/2002GL015640, 2002.

1. Introduction

[2] Sunspot numbers form the longest directly observed index of solar activity (SA) and are thus extremely important for the study of solar magnetism. Some exceptional periods exist in sunspot observations, in particular the so-called great minima of solar activity. Another type of an exceptional period is the Dalton minimum (DM) at the turn of 18th and 19th century during which sunspot cycle evolution experienced an unusual behaviour known as the phase catastrophe [e.g., *Sonett*, 1983; *Wilson*, 1988; *Kremliovsky*, 1994]. These results were based on the Wolf sunspot series which contains, however, hidden interpolation during times of observational gaps. Instead, we use the new group sunspot series [*Hoyt and Schatten*, 1998] which is more consistent and homogeneous than the Wolf sunspot series for the time before 1850 [*Hoyt and Schatten*, 1998; *Letfus*, 1999; *Serre and Nesme-Ribes*, 2000] and contains original (not interpolated or preprocessed) data of daily sunspot observations by individual observers. Unfortunately, the years 1790–1794 at the beginning of DM were very poorly covered by sunspot observations. Therefore, the Wolf series might have large uncertainties during that period [*Hoyt and Schatten*, 1998; *Letfus*, 1999]. As a result of a detailed analysis of the group sunspot series, we have recently suggested [*Usoskin et al.*, 2001] that one small cycle was likely lost in 1790's because of sparse and partly unreliable sunspot observations. This cycle (called the new cycle throughout the paper) is formed from the abnormally long declining phase of the standard solar cycle 4. Unfortunately, the lack of more complete solar observations during that period denies to verify this hypothesis directly. However, in this paper we study the possibility of the new cycle in two frequently used sets of indirect solar proxies, visual aurorae and cosmogenic isotopes, and discuss in detail the consequences of the new cycle for solar activity.

2. Lost Cycle in Sunspot Data

[3] The period at the start of the Dalton minimum was poorly covered by sunspot observations. E.g., in 1792 sunspot observations were made only during 4 days. Also, the accuracy of daily sunspot numbers was rather poor during that period. We have recently performed a detailed analysis of daily sunspot observations taking into account the reliability of each individual observer and suggested that one small solar cycle (SC) was probably lost in 1790's [*Usoskin et al.*, 2001]. An approximate profile of the suggested sunspot activity in 1790's is shown in Figure 1a together with the actual monthly GSN data and the standard yearly group sunspot number series. According to our suggestion, the exceptionally long cycle starting in 1784 (former SC 4) is now numbered as SC 3′ and ends in 1793. It was evolving regularly until declining rather rapidly to a minimum in 1793, followed by the new weak cycle which was missed earlier. This new cycle is now numbered as SC 4′, and it starts the Dalton minimum. Table 1 shows the estimated minimum and maximum times of the solar cycles around DM using the standard and new cycle numbering.

[4] We note that the time profile of the new cycle depicted in Figure 1a is only qualitative because the sparseness of sunspot observations does not allow to determine it exactly. Strictly taken, only other, more reliable sunspot observations, or the latitudinal distribution of sunspots and the reconstruction of the Maunder butterfly diagram in 1790s could prove or disprove the existence of the lost cycle. Unfortunately, such information is not known to exist. However, geomagnetic or heliospheric parameters that depend on solar activity may yield independent, though less direct information about the possible new cycle.

3. Indirect Proxies

3.1. Auroral Observations

[5] Visual auroral observations are commonly used as an indirect proxy of SA for early times [see, e.g. *Silverman*,

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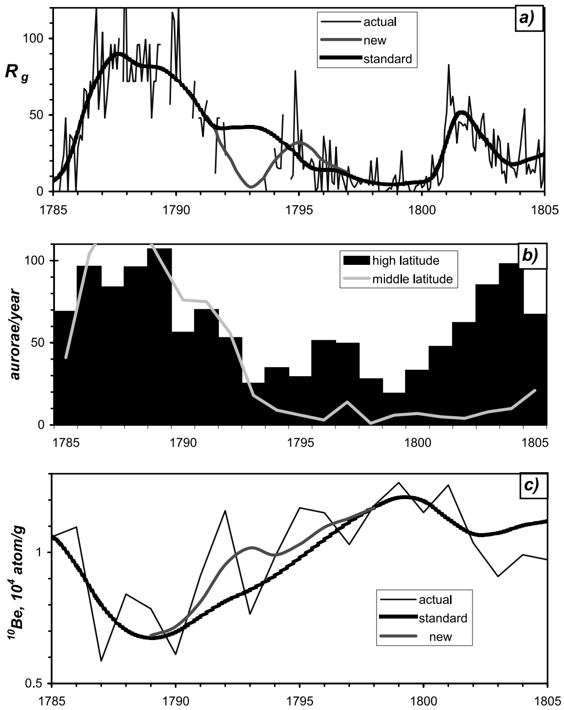

Figure 1. Solar and geomagnetic activity and cosmic rays in the beginning of the Dalton minimum. a) Sunspot activity: actual monthly (thin line) and standard yearly (thick line) group sunspot numbers [*Hoyt and Schatten*, 1998], and the suggested profile (grey curve) [*Usoskin et al.*, 2001]. b) Yearly number of visual aurorae at high (bars) [*Silverman*, 1983] and middle (grey curve) [*Křivský and Pejml*, 1988] latitudes. c) Data on cosmogenic ^{10}Be in polar ice: actual annual content of ^{10}Be in Greenland (thin line) [*Beer et al.*, 1990], together with the expected ^{10}Be response for the standard (thick curve) and new suggested profiles of solar activity (grey curve) corresponding to panel a).

1983]. Auroral observations from two data sets are shown in Figure 1b for the period studied. Black bars correspond to the annual series of aurorae in Sweden (latitude about 60°) according to the Rubenson catalogue [*Silverman*, 1983]. Grey line depicts the annual series of aurorae observed at middle latitudes (<55°) in central Europe [*Křivský and Pejml*, 1988]. Note first the difference in overall activity level between the two auroral data sets. While the high-latitude auroral activity roughly retains its level even within the Dalton minimum, the mid-latitude activity is greatly reduced during DM. This is understandable since the high-latitude auroral activity responses even to small geomagnetic disturbances while the occurrence of mid-latitude auroras requires large storms. However, both auroral data sets show a significant and concurrent decrease of auroral activity in early 1790's. Such a dramatic decrease can not be understood if solar activity was as high as given by the Wolf sunspot numbers. On the other hand, this decrease corresponds very well with the suggested additional SA minimum in 1793.

[6] Despite the difference in the overall activity level, the two auroral data sets demonstrate quite a similar detailed structure over the time interval depicted in Figure 1b. In particular, both data sets have a clear, separate maximum in the declining phase of the new SC 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 SC 5. This shows that large geomagnetic storms were quite rare during the whole Dalton minimum. Note also that the auroral maximum of SC 4′ occurs 1–2 years after the sunspot maximum which is typical for most solar cycles. However, if this maximum would be part of the exceptionally long SC 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.

3.2. Cosmogenic Isotopes

[7] Another commonly used proxy of solar activity is the abundance of cosmogenic isotopes in natural archives. Cosmogenic isotopes are produced in the Earth's atmosphere by cosmic rays which suffer from the heliospheric modulation, leading to the overall anti-correlation of cosmogenic isotopes with solar activity. Cosmogenic ^{10}Be isotope is believed to be a good proxy of long-term solar activity [see, e.g., *Beer et al.*, 1990; 2000], but the short-term solar activity is less accurately reproduced. In order to check if the lost cycle could be seen in ^{10}Be data, we performed the following calculations (similar to [*Usoskin et al.*, 2002]). First we calculated the expected interplanetary magnetic field (IMF) for the two different time profiles of sunspot activity in 1784–1800 (see Figure 1a), using the empirical model by *Solanki et al.* [2000]. Then, using this IMF profile as an input for a model of the heliosphere [*Usoskin et al.*, 2002] we calculated the expected cosmic ray flux and the ensuing ^{10}Be production rate at the Earth. The two calculated ^{10}Be profiles are shown in Figure 1c together with the actually measured content of ^{10}Be in Greenland ice [*Beer et al.*, 1990]. Note first the overall agreement between the predicted and actually recorded ^{10}Be data which supports the adequacy of the employed model. Although a slightly better fit to data is obtained by the model including the new cycle, the calculated difference in ^{10}Be production between the standard and the new sunspot profiles is small and evidently below the uncertainty of ^{10}Be measurements. Therefore, ^{10}Be data do not allow to distinguish between the two cases and do not confirm or deny the existence of the new cycle. Note also that another commonly used cosmogenic isotope, radiocarbon ^{14}C, is even less sensitive to rapid changes than ^{10}Be because of its long attenuation time in large terrestrial reservoirs [*Bard et al.*, 1997], and accordingly, can not resolve the lost cycle. Therefore, the

Table 1. Years of Minimum and Maximum of Sunspot Cycles Around the Dalton Minimum

Old numbering			New numbering		
SC	min	max	SC	min	max
4	1784.3	1788.4	3′	1784.3	1788.4
			4′	1793.1[a]	1795.0[a]
5	1798.7	1802	5	1799.8[a]	1802.5[a]
6	1810.8	1817.1	6	1810.8	1817.1
7	1823.0	1829.6	7	1823.0	1829.6

[a]Suggested estimate [*Usoskin et al.*, 2001].

existence of the lost cycle is neither supported nor contradicted by the available data on cosmogenic isotopes.

4. Consequences of the Lost Cycle

[8] The existence of the new cycle has important consequences for the evolution of sunspot activity which can be divided into direct consequences and changes of statistical features of solar cycles.

4.1. Direct Consequences

[9] The unusual behaviour of SA evolution around 1800 was mentioned by many earlier researchers E.g., *Rozelot* [1994] reported on bad multiharmonic representation of sunspot activity around 1800. *Sonett* [1983] and *Wilson* [1988] mentioned on apparent inconsistency of the sunspot record during that period. This unusual SA evolution was attributed to a phase catastrophe of solar activity which was seen as a distortion of the solar cycle shape in 1790–1794 [*Vitinsky et al.*, 1986; *Kremliovsky*, 1994], when the phase evolution of SA was nearly linear rather than cyclic. It was believed earlier that the Dalton minimum had no clear start, in contrast to the Maunder minimum, and that the Sun entered DM through the phase catastrophe [*Kremliovsky*, 1994]. Accordingly, it was suggested that a phase catastrophe might be a precursor of a great minimum [*Kremliovsky*, 1994; *Polygiannakis et al.*, 1996]. However, the Maunder minimum in 1645–1715 has a different scenario with no apparent precursor: sharp decline of a regular high cycle to zero activity followed by a gradual restoration of the activity [*Usoskin et al.*, 2000].

[10] With including the new cycle, the phase evolution of SA changes significantly around the Dalton minimum. First of all, the phase catastrophe disappears since two regular cycles are formed instead of an extended linear declining phase of SC 4. With the new cycle, the scenario of DM becomes clearer: a normal high cycle (SC 3′ in the new numbering) with a sharp declining phase is followed by a small cycle (SC 4′) which is the first and smallest cycle of DM marking a clear start of the Dalton minimum in 1793. Subsequent cycles are increasingly intensive. Note that this behaviour closely resembles the scenario of the Maunder minimum [*Usoskin et al.*, 2000]: an abrupt decline of a normal cycle followed by a gradual restoration of activity.

[11] Thus, both these intervals of exceptionally weak solar activity covered by direct observations demonstrate a very similar overall scenario.

4.2. Statistical Features of Solar Cycles

[12] The well-known Gnevyshev-Ohl (GO) rule [e.g., *Gnevyshev and Ohl*, 1948; *Wilson*, 1988] orders sunspot cycles to even-odd pairs so that the intensity (sum of monthly sunspot numbers over the cycle) of the odd cycle is larger than that of the preceding even cycle. 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. It was shown recently [*Mursula et al.*, 2001] that a persistent 22-year cyclicity, which exists in sunspot cycle intensity, is responsible for the empirical GO rule. Note that while this 22-year cycle is persistent in phase throughout the entire interval since 1610, the GO rule suffers a phase-reversal around DM [*Mursula et al.*, 2001]. It is important that the observed 22-year cyclicity,

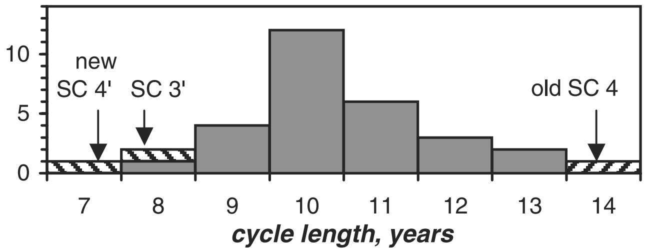

Figure 2. Distribution of solar cycle lengths for all solar cycles except for 1784–1799 (grey bars). Right hatched bar corresponds to the old SC 4, and left hatched bars correspond to the new SC 3′ and SC 4′.

resulting from a continuous analysis of the GSN time series, is independent of cycle definition, while the GO rule depends on the numbering of cycles. As discussed in [*Usoskin et al.*, 2000], including the new cycle shifts the numbering of cycles before DM so that odd cycles become even and vice versa, which is equal to a phase reversal of GO rule. Therefore, the new cycle restores the important empirical GO rule, which is then valid throughout the entire 400-year interval of sunspot observations.

[13] The length of solar cycle varies around the mean value of 10.7 years as shown in Figure 2. (We have determined solar minima as minima of the 12-month running mean of the GSN series.) Grey bars depict the distribution for all solar cycles included in the GSN series except for those under investigation. The extremely long SC 4 (14.5 years) corresponds to the right hatched bar. Including the new cycle splits this cycle into two shorter cycles (reasonably short SC 3′ and extremely short SC 4′) corresponding to the two left hatched bars. One can see that neither the old SC 4 nor new sunspot cycles are detached from the distribution or change it notably. Therefore, the new cycle does not distort the cycle length distribution with respect to the standard cycle numbering. Rather, it makes the distribution slightly more symmetric around the mean cycle length of 10.7 years.

[14] The so-called Waldmeier effect relates the amplitude of a solar cycle to the length of its phases [e.g., *Waldmeier*, 1960; *Vitinsky et al.*, 1986, and the references therein]. The overall anti-correlation between cycle amplitude and ascending phase (see Figure 3a) is quite strong ($r = -0.6 \pm 0.2$) for all cycles using the standard cycle numbering. The new SC 4′ is shown as a grey dot in Figure 3a. Since the suggested time profile of the new cycle is only qualitative, the times and level of its maximum/minimum activity are rather imprecise and only a range can be given. The new cycle clearly lies aside of the main relation and makes the overall anti-correlation slightly worse ($r = -0.52 \pm 0.25$). However, note that other cycles corresponding to great minima (SC −5 in 1700–1712 and SC 5 in 1799–1811) are equally bad outliers, and the new SC 4′ resembles these greatly (Figure 3a). In fact, these three cycles seem to form a similar overall anti-correlation as the majority of cycles but with a suppressed cycle amplitude. This is in accord with our recent results [*Usoskin et al.*, 2001a] that the features of the solar cycle are essentially similar, except for the activity level, during times of normal high activity and during great minima. On the other hand, the length of

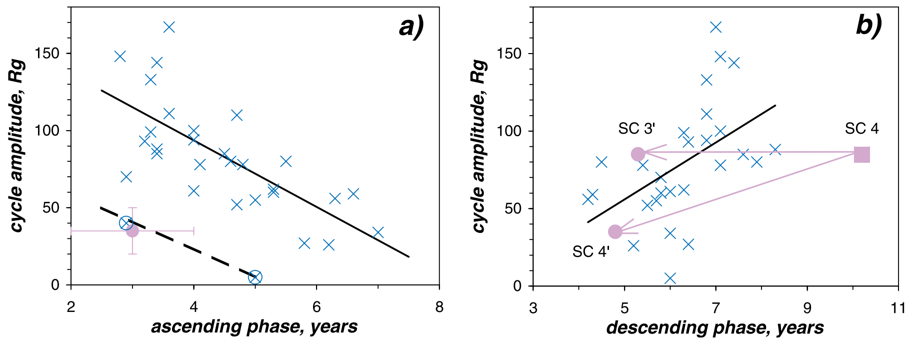

Figure 3. Scatter plot of amplitude vs. length of solar cycle phases. The lines give the best fit linear relations. a) Ascending phase. The new SC 4′ is depicted by the grey dot. Other exceptional cycles (SC −5 and SC 5) are marked by circled crosses. Solid and dashed lines correspond to the linear relation for all and only minimum-like cycles, respectively. b) Descending phase. Old SC 4 and new cycles SC 3′ and SC 4′ are marked in grey.

descending phase correlates positively with cycle amplitude (see Figure 3b). For the standard cycle numbering, the correlation is $r = 0.43 \pm 0.22$. One can see that the old SC 4 lies far aside of the relation because of its exceptionally long descending phase. When including the new cycle, two cycles with more normal descending phases are formed instead of SC 4 as shown in Figure 3b. This makes the formal correlation stronger, $r = 0.53 \pm 0.20$. Overall, there is a weak negative relation between the cycle amplitude and the total cycle length ($r = -0.3 \pm 0.2$ for the standard cycle numbering). Including the new cycle hardly changes this relation ($r = -0.27 \pm 0.2$). Therefore, the new cycle does not change the cycle length distribution and only slightly modifies the formal anti-correlation in the Waldmeier effect.

5. Conclusions

[15] We have tested the hypothesis of the existence of a small lost cycle in the beginning of the Dalton minimum [*Usoskin et al.*, 2001] using available indirect data on solar activity. We have shown that geomagnetic data (visual aurorae at middle and high latitudes) provides new strong independent evidence in favor of the new cycle. Moreover, we have shown that the new cycle does not contradict to the available cosmogenic isotope data. Therefore, this cycle is supported by (or at least does not contradict to) all available solar proxies with short-time resolution. We have discussed the important consequences of the new cycle for solar activity. The new cycle resolves the problem of a phase catastrophe at the turn of 18th and 19th centuries. 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, which may be a general scenario of the start of a great minimum. The new cycle restores the Gnevyshev-Ohl rule across the Dalton minimum making it valid throughout the entire 400 years of sunspot observations. We have also discussed that the new cycle, while leading to a consistent view of solar activity evolution, does not distort the known cycle length distribution or the Waldmeier relations for the sake of the above improvements.

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