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A SOLAR CYCLE LOST IN 1793–1800: EARLY SUNSPOT OBSERVATIONS RESOLVE THE OLD MYSTERY

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ABSTRACT

Because of the lack of reliable sunspot observations, the quality of the sunspot number series is poor in the late 18th century, leading to the abnormally long solar cycle (1784–1799) before the Dalton minimum. Using the newly recovered solar drawings by the 18–19th century observers Staudacher and Hamilton, we construct the solar butterfly diagram, i.e., the latitudinal distribution of sunspots in the 1790s. The sudden, systematic occurrence of sunspots at high solar latitudes in 1793–1796 unambiguously shows that a new cycle started in 1793, which was lost in the traditional Wolf sunspot series. This finally confirms the existence of the lost cycle that has been proposed earlier, thus resolving an old mystery. This Letter brings the attention of the scientific community to the need of revising the sunspot series in the 18th century. The presence of a new short, asymmetric cycle implies changes and constraints to sunspot cycle statistics, solar activity predictions, and solar dynamo theories, as well as for solar-terrestrial relations.

Key words: Sun: activity – sunspots

1. INTRODUCTION

Starting from the first telescopic sunspot observations by David and Johannes Fabricius, Galileo Galilei, Thomas Harriot, and Christoph Scheiner, the 400 year sunspot record is one of the longest directly recorded scientific data series, and forms the basis for numerous studies in a wide range of research such as, e.g., solar and stellar physics, solar-terrestrial relations, geophysics, and climatology. During the 400 year interval, sunspots depict a great deal of variability from the extremely quiet period of the Maunder minimum (Eddy 1976) to the very active modern time (Solanki et al. 2004). The sunspot numbers also form a benchmark data series, upon which virtually all modern models of long-term solar dynamo evolution, either theoretical or (semi-)empirical, are based. Accordingly, it is important to review the reliability of this series, especially since it contains essential uncertainties in the earlier part.

The first sunspot number series was introduced by Rudolf Wolf who observed sunspots from 1848 until 1893, and constructed the monthly sunspot numbers since 1749 using archival records and proxy data (Wolf 1861). Sunspot activity is dominated by the 11 year cyclicity, and the cycles are numbered in Wolf's series to start with cycle 1 in 1755. When constructing his sunspot series Wolf interpolated over periods of sparse or missing sunspot observations using geomagnetic proxy data, thus losing the actual detailed temporal evolution of sunspots (Hoyt et al. 1994; Hoyt & Schatten 1998). Sunspot observations were particularly sparse in the 1790s, during solar cycle 4 which became the longest solar cycle in Wolf's reconstruction with an abnormally long declining phase (see Figure 1(a)). The quality of Wolf's sunspot series during that period has been questioned since long. Based on independent auroral observations, it was proposed by Elias Loomis already in 1870 that one small solar cycle may have been completely lost in Wolf's sunspot reconstruction in the 1790s (Loomis 1870), being hidden inside the interpolated, exceptionally long declining phase of solar cycle 4. This extraordinary idea was not accepted at that time. A century later, possible errors in Wolf's compilation for the late 18th century have been emphasized again based on detailed studies of Wolf's sunspot series (Gnevyshev & Ohl 1948; Sonett 1983).

Recently, a more extensive and consistent sunspot number series (Figure 1(b)), the group sunspot numbers (GSNs), was introduced by Hoyt & Schatten (1998), which increases temporal resolution and allows us to evaluate the statistical uncertainty of sunspot numbers. We note that the GSN series is based on a more extensive database than Wolf's series and explicitly includes all the data collected by Wolf. However, it still depicts large data gaps in 1792–1794 (this interval was interpolated in Wolf's series). Based on a detailed study of the GSN series, Usoskin et al. (2001b, 2002) revived Loomis' idea by showing that the lost cycle (a new small cycle started in 1793, which was lost in the conventional Wolf sunspot series) agrees with both the GSN data (Figure 1(b)) and indirect solar proxies (aurorae) and does not contradict with the cosmogenic isotope data. However, using time series analysis of sparse sunspot counts or sunspot proxies, it is hardly possible to finally verify the existence of the lost solar cycle. Therefore, the presence of the lost cycle has so far remained an unresolved issue.

Here we analyze newly restored original solar drawings of the late 18th century to ultimately resolve the old mystery and to finally confirm the existence of the lost cycle.

2. DATA AND ANALYSIS

2.1. Positional Sunspot Data

Most of Wolf's sunspot numbers in 1749–1796 were constructed from observations by the German amateur astronomer Johann Staudacher who not only counted sunspots but also drew solar images in the second half of the 18th century (see an example in Figure 2). However, only sunspot counts have so far been used in the sunspot series, but the spatial distribution of spots in these drawings has not been analyzed earlier. The first analysis of this data, which covers the lost cycle period in 1790s, has been made only recently (Arlt 2008) using Staudacher's original drawings. Additionally, a few original solar disk drawings made by the Irish astronomer James Archibald Hamilton and his assistant since 1795 have been recently found in the archive of the Armagh Observatory (Arlt 2009b). After the digitization and processing of these two sets of original drawings (Arlt 2008, 2009a, 2009b), the location of individual sunspots on the solar

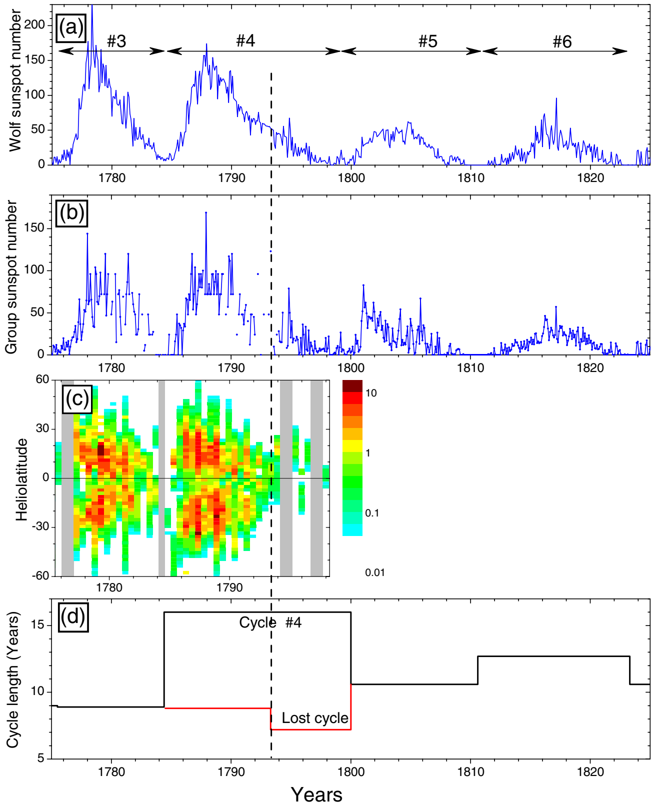

Figure 1. Sunspot activity in the late 18th and early 19th century. The start of the lost cycle (late 1793) is denoted by a vertical dashed line. (a): monthly Wolf sunspot numbers with conventional solar cycle numbers shown on the top. (b): monthly GSNs. (c): the newly reconstructed sunspot butterfly diagram, which takes into account the uncertainties of the estimate sunspot latitudes. The color scale on the right gives the density (in year^{-1} deg^{-1}) of sunspots in latitude-time bins (one bin covers 2° in latitude and six months in time). Gray bars indicate that no latitudinal information is available for the corresponding half-year. (d): lengths of solar cycles. The conventional lengths using the GSNs are shown by the black line, while the red line depicts the cycle lengths after including the lost cycle.

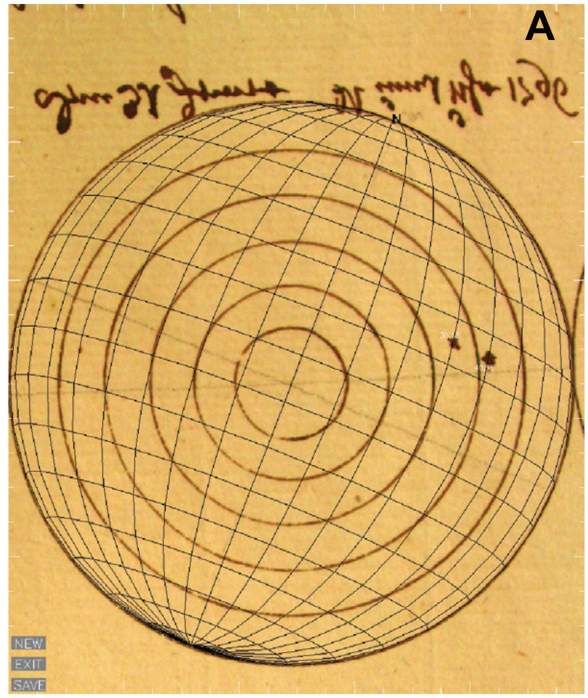

Figure 2. Example of drawings of sunspots on the solar disk made by Staudacher in Nürnberg, Germany at 1 p.m. local time on 1796 January 31. The image is mirrored to correspond to the real view to the solar disk. The heliographical grid has been included during the image processing (Arlt 2009a).

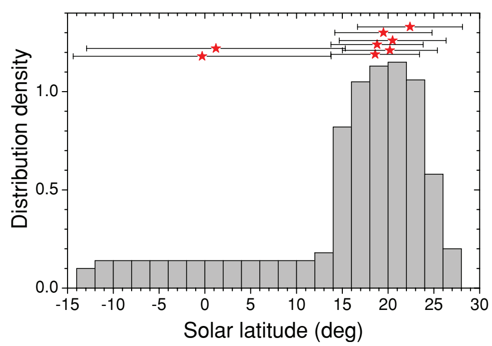

Figure 3. Example of the sunspot latitudinal distribution for 1793 July–December, with 2° latitudinal bins. Stars with error bars denote latitudes of individual spots as defined from Staudacher's drawings. The histogram depicts the density of the latitudinal distribution of sunspots per 2° bins per half-year computed by including the uncertainties.

disc in the late 18th century has been determined. This makes it possible to construct the sunspot butterfly diagram for solar cycles 3 and 4 (Figure 1(c)), which allows us to study the existence of the lost cycle more reliably than based on sunspot counts only.

2.2. Constructing the Butterfly Diagram from Data with Uncertainties

Despite the good quality of original drawings, there is an uncertainty in determining the actual latitude for some sunspots (see Arlt 2009a, 2009b for details). This is related to the limited information on the solar equator in these drawings. The drawings which are mirrored images of the actual solar disc as observed from Earth cannot be analyzed by an automatic procedure adding the heliographic grid. Therefore, special efforts have been made to determine the solar equator and to place the grid of true solar coordinates for each drawing (see Figure 2). Depending on the information available for each drawing, the uncertainty in defining the solar equator, ΔQ, ranges from almost 0° up to a maximum of 15° (Arlt 2009a). The latitude error of a sunspot, identified to appear at latitude λ, can be defined as

$$\Delta_\lambda = \Delta Q \cdot \sin(\alpha) \quad (1)$$

where ΔQ is the angular uncertainty of the solar equator in the respective drawing, and α is the angular distance between the spot and the solar disc center. Accordingly, the final uncertainty Δ_λ can range from 0° (precise definition of the equator or central location of the spot) up to 15°. We take the uncertain spot location into account when constructing the semiannually averaged butterfly diagram as follows. Let us illustrate the diagram construction for the second half-year (July–December) of 1793 (Figure 3). During this period there were only two daily drawings by Staudacher with the total of eight sunspots: two spots on August 6, which were located close to the limb near the equator, and six spots on November 3, located near the disk center at higher latitudes. The uncertainty in definition of the equator was large ($\Delta Q = 15°$) for both drawings. Because of the near-limb location (large α) of the first two spots, the error Δ_λ of latitude definition (Equation (1)) is quite large. The high-latitude spots of the second drawing are more precisely determined because of the central location of the spots. The latitudinal occurrence of these eight spots and their uncertainties are shown in Figure 3 as stars with error bars. The true position of a spot is within the latitudinal band $\lambda \pm \Delta_\lambda$, where Δ_λ is regarded as an observational error and λ as the formal center of the latitudinal band. Accordingly, when constructing the butterfly diagram, we spread the occurrence of each spot within this latitudinal band with equal probability (the use of other distribution does not affect the result). Finally, the density of the latitudinal distribution of spots during the analyzed period is computed as shown by the histogram in Figure 3. This density is the average number of sunspots occurring per half-year per 2° latitudinal bin. Each vertical column in the final butterfly diagram shown in Figure 1(c) is in fact such a histogram for the corresponding half-year.

2.3. *Statistical Test*

Typically, the sunspots of a new cycle appear at rather high latitudes of about 20°–30°. This takes place around the solar cycle minimum. Later, as the new cycle evolves, the sunspot emergence zone slowly moves towards the solar equator. This recurrent "butterfly"-like pattern of sunspot occurrence is known as the Spörer law (Maunder 1904) and is related to the action of the solar dynamo (see, e.g., Charbonneau 2005). It is important that the systematic appearance of sunspots at high latitudes unambiguously indicates the beginning of a new cycle (Waldmeier 1975) and thus may clearly distinguish between the cycles.

One can see from the reconstructed butterfly diagram (Figure 1(c)) that the sunspots in 1793–1796 appeared dominantly at high latitudes, clearly higher than the previous sunspots that belong to the late declining phase of the ending solar cycle 4. Thus, a new "butterfly" wing starts in late 1793, indicating the beginning of the lost cycle.

Since sunspot observations are quite sparse during that period, we have performed a thorough statistical test as follows. The location information of sunspot occurrence on the original drawings during 1793–1796 (summarized in Table 1) allows us to test the existence of the lost cycle. The observed sunspot latitudes were binned into three categories: low (<8°), mid (8°–16°), and high latitudes (>16°), as summarized in Column 2 of Table 2. We use all available data on latitude distribution of sunspots since 1874 covering solar cycles 12–23 (The combined Royal Greenwich Observatory (1874–1981) and USAF/NOAA (1981–2007) Sunspot Data set: http://solarscience.msfc.nasa.gov/greenwch.shtml) as the reference data set. We tested first if the observed latitude distribution of sunspots (three daily observations with low-latitude spots, one with mid-latitude and three with only high-latitude spots; see Table 2) is consistent with a late declining phase (D-scenario, i.e., the period 1793–1796 corresponds to the extended declining phase of cycle 4) or with the early ascending phase (A-scenario, i.e., the period 1793–1796 corresponds to the ascending phase of the lost cycle). We have selected two subsets from the reference data set: D-subset corresponding to the declining phase which covers three last years of solar cycles 12–23 and includes in total 11,235 days when 33,803 sunspot regions were observed; and A-subset corresponding to the early ascending phase which covers three first years of solar cycles 13–23 and includes 10,433 days when 47,096 regions were observed.

First we analyzed the probability to observe sunspot activity of each category on a randomly chosen day. For example, we found in the D-subset 4290 days when sunspots were observed at low latitudes below 8°. This gives the probability $p = 0.38$ (see first line, Column 3 in Table 2) to observe such a pattern on a random day in the late decline phase of a cycle. Similar probabilities for the other categories in Table 2 have been computed in the same way. Next we tested whether the observed low-latitude spot occurrence (three out of seven daily observations) corresponds to declining/ascending phase scenario. The corresponding probability to observe n events (low-latitude spots) during m trials (observational days) is given as

$$P_m^n = p^n \cdot (1-p)^{m-n} \cdot C_m^n, \qquad (2)$$

where p is the probability to observe the event at a single trial, and C_m^n is the number of possible combinations. We assume here that the results of individual trials are independent of each other, which is justified by the long separation between observational days. Thus, the probability to observed three low-latitude spots during seven random days is $P_7^3 = 0.27$ and 0.07 for D- and A-hypotheses, respectively. The corresponding probabilities are given in the first row, Columns 5–6 of Table 2. The occurrence of three days with low latitude activity is quite probable for both declining and ascending phases. Thus, this criterion cannot distinguish between the two cases. The observed mid-latitude spot occurrence (one out of seven daily observations) is also consistent with both D- and A-scenarios. The corresponding confidence levels (0.06 and 0.22, respectively, see the second row, Columns 5–6 of Table 2) do not allow us to select between the two hypotheses. Next we tested the observed high-latitude spot occurrence (three out of seven observations) in the D/A-scenarios (the corresponding probabilities are given in the third row of Table 2). The occurrence of three days with high-latitude activity is highly improbable during a late declining phase (D-scenario). Thus, the hypothesis of the extended cycle 4 is rejected at the level of 5×10^{-4}. The A-scenario is well consistent (confidence 0.26) with the data. Thus, the observed high-latitude sunspot occurrence clearly confirms the existence of the lost cycle.

We also noticed that sunspots tend to appear in the northern hemisphere (13 out of 16 observed sunspots appeared in the northern hemisphere). Despite the rather small number

Table 1
Sunspot Occurrence During the Lost Cycle with Dates, Number (N), and Latitude Range (λ) of the Observed Spots on Each Day

Date and Observer	N	λ
1793.08.06 Staudacher	2	<3°
1793.11.03 Staudacher	6	>18° N
1795.02.19 Staudacher	3	>20° N
1795.10.08–15 Hamilton	2	15° S and 6° N
1795.11.02–03 Hamilton	1	5.5° S
1796.01.31[a] Staudacher	2	>16° N

Note.
[a] Shown in Figure 2.

Table 2
Number of Days (n) with Observed Sunspots in 1793–1796, Sunspot Latitude Ranges, Probability (p) of Sunspots Found on a Randomly Selected Day, and the Cumulative Probability (P), Calculated for D- and A-scenaria Using All Data Since 1874

n	Latitude Range	Probability p		Cumulative Probability P	
		D-scenario	A-scenario	D-scenario	A-scenario
3	Low latitude (<8°)	0.38	0.1	0.27	0.07
1	Mid-latitude (8–16°)	0.48	0.32	0.06	0.22
3	High latitude (>16°)	0.026	0.52	0.0005	0.26

of observations, the statistical significance of asymmetry is quite good (confidence level 99%), i.e., it can be obtained by chance with the probability of only 0.01, in a purely symmetric distribution. Nevertheless, more data are needed to clearly evaluate the asymmetry.

Thus, a statistical test of the sunspot occurrence during 1793–1796 confirms that:

1. The sunspot occurrence in 1793–1796 contradicts with a typical latitudinal pattern in the late declining phase of a normal solar cycle (at the significance level of 5×10^{-4}).
2. The sunspot occurrence in 1793–1796 is consistent with a typical ascending phase of the solar cycle, confirming the start of the lost solar cycle. We note that it has been shown earlier (Usoskin et al. 2003), using the GSN, that the sunspot number distribution during 1792–1793 was statistically similar to that in the minimum years of a normal solar cycle, but significantly different from that in the declining phase.
3. The observed asymmetric occurrence of sunspots during the lost cycle is statistically significant (at the significance level of 0.01).

Therefore, the sunspot butterfly diagram (Figure 1(c)) unambiguously proves the existence of the lost cycle in the late 18th century, verifying the earlier evidence based on sunspot numbers (Usoskin et al. 2001b, 2003) and aurorae borealis (Loomis 1870; Usoskin et al. 2002).

3. DISCUSSION AND CONCLUSIONS

An additional cycle in the 1790s changes cycle numbering before the Dalton minimum, thus verifying the validity of the *Gnevyshev-Ohl* rule of sunspot cycle pairing (Gnevyshev & Ohl 1948) and the related 22 year periodicity (Mursula et al. 2001) in sunspot activity throughout the whole 400 year interval. Another important consequence of the lost cycle is that, instead of one abnormally long cycle 4 (min-to-min length ≈15.5 years according to GSN (Usoskin et al. 2002)) there are two shorter cycles of about 9 and 7 years (see Figure 1(d)). Note also that some physical dynamo models even predict the existence of cycles of small amplitude and short duration near a grand minimum (Küker et al. 1999). Cycle 4 (1784–1799 in GSN) with its abnormally long duration dominates empirical studies of relations, e.g., between cycle length and amplitude. Replacing an abnormally long cycle 4 by one fairly typical and one small short cycle changes empirical relations based on cycle length statistics. This will affect, e.g., predictions of future solar activity by statistical or dynamo-based models (Dicke 1978; Dikpati et al. 2006; Brajša et al. 2009), and some important solar-terrestrial relations (Friis-Christensen & Lassen 1991; Kelly & Wigley 1992).

The lost cycle starting in 1793 depicts notable hemispheric asymmetry with most sunspots of the new cycle occurring in the northern solar hemisphere (Figure 1(c)). This asymmetry is statistically significant at the confidence level of 99%. A similar, highly asymmetric sunspot distribution existed during the Maunder minimum of sunspot activity in the second half of the 17th century (Soon & Yaskel 2003; Ribes & Nesme-Ribes 1993). However, the sunspots during the Maunder minimum occurred preferably in the southern solar hemisphere (Sokoloff & Nesme-Ribes 1994), i.e., opposite to the asymmetry of the lost cycle. This shows that the asymmetry is not constant, contrary to some earlier models involving the fossil solar magnetic field (Bravo & Stewart 1995; Boruta 1996; Usoskin et al. 2001a). Interestingly, this change in hemispheric asymmetry between the Maunder and Dalton minimum is in agreement with an earlier, independent observation, based on long-term geomagnetic activity, that the north–south asymmetry oscillates at the period of about 200–250 years (Mursula & Zieger 2001).

Concluding, the newly recovered spatial distribution of sunspots of the late 18th century conclusively confirms the existence of a new solar cycle in 1793–1800, which has been lost under the preceding, abnormally long cycle compiled by Rudolf Wolf when interpolating over the sparse sunspot observations of the late 1790s. This Letter brings the attention of the scientific community to the need for revising the sunspot series in the 18th century and the solar cycle statistics. This emphasizes the need to search for new, yet unrecovered, solar data to restore details of solar activity evolution in the past (e.g., Vaquero 2007). The new cycle revises the long-held sunspot number series, restoring its cyclic evolution in the 18th century and modifying the statistics of all solar cycle related parameters. The northern dominance of sunspot activity during the lost cycle suggests that hemispheric asymmetry is typical during grand minima of solar activity, and gives independent support for a systematic, century-scale oscillating pattern of solar hemispheric asymmetry. These results have immediate practical and theoretical consequences, e.g., to predicting future solar activity and understanding the action of the solar dynamo.

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