Thaddäus Derfflinger’s Sunspot Observations during 1802–1824: A Primary Reference to Understand the Dalton Minimum

Hisashi Hayakawa1,2,3,10, Bruno P. Besser4,5, Tomoya Iju6, Rainer Arlt7, Shoma Uneme8, Shinsuke Imada8, Philippe-A. Bourdin4,5, and Amand Kraml9

1 Graduate School of Letters, Osaka University, 5600043, Toyonaka, Japan; hayakawa@kwasan.kyoto-u.ac.jp, hisashi.hayakawa@stfc.ac.uk
2 UK Solar System Data Centre, Space Physics and Operations Division, RAL Space, Science and Technology Facilities Council, Rutherford Appleton Laboratory, Harwell Oxford, Didcot, Oxfordshire, OX11 0QX, UK
3 Nishina Center, RIKEN, Wako, 3510198, Japan
4 Space Research Institute, Austrian Academy of Sciences, Graz, A-8042, Austria
5 Institute of Physics, University of Graz, A-8010 Graz, Austria
6 National Astronomical Observatory of Japan, 1818588, Mitaka, Japan
7 Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, D-14482 Potsdam, Germany
8 Institute for Space-Earth Environmental Research, Nagoya University, 4648601, Nagoya, Japan
9 Sternwarte, Stift Kremsmünster, A-4550, Kremsmünster, Austria

Received 2019 November 18; revised 2019 December 13; accepted 2019 December 23; published 2020 February 17

Abstract

As we are heading toward the next solar cycle, presumably with a relatively small amplitude, it is of significant interest to reconstruct and describe the past secular minima on the basis of actual observations at the time. The Dalton Minimum is often considered one of the secular minima captured in the coverage of telescopic observations. Nevertheless, the reconstructions of the sunspot group number vary significantly, and the existing butterfly diagrams have a large data gap during the period. This is partially because most long-term observations at that time have remained unexplored in historical archives. Therefore, to improve our understanding on the Dalton Minimum, we have located two series of Thaddäus Derfflinger’s observational records spanning 1802–1824. We have revisited the existing Derfflinger’s sunspot group number with Waldmeier classification, and eliminated all the existing “spotless days” to remove contaminations from solar elevation observations. We have reconstructed the butterfly diagram on the basis of his observations and illustrated sunspot distributions in both solar hemispheres. Our article aims to revise the trend of Derfflinger’s sunspot group number and to bridge a data gap of the existing butterfly diagrams around the Dalton Minimum. Our results confirm that the Dalton Minimum is significantly different from the Maunder Minimum, both in terms of cycle amplitudes and sunspot distributions. Therefore, the Dalton Minimum is more likely a secular minimum in the long-term solar activity, while further investigations for the observations at that time are required.

Unified Astronomy Thesaurus concepts: Solar magnetic fields (1503); Sunspot cycle (1650); Solar cycle (1487); Sunspots (1653); Solar-terrestrial interactions (1473); Stellar activity (1580); Astronomy databases (83)

1. Introduction

It is important to investigate and reconstruct solar activity of the past, as it provides fundamental input for several fields, such as the solar dynamo theory (Charbonneau 2010; Arlt & Weiss 2014; Augustson et al. 2015; Hotta et al. 2016), the solar–terrestrial relationship (Lockwood 2013; Hayakawa et al. 2018a, 2019b), space weather (Cliver & Dietrich 2013; Hayakawa et al. 2017, 2018d, 2019a; Toriumi et al. 2017; Toriumi & Wang 2019), space climate (Hathaway & Wilson 2004; Barnard et al. 2011; Owens et al. 2011; Usoskin et al. 2015; Hayakawa et al. 2019c; Pavlov et al. 2019), terrestrial climate change (Gray et al. 2010; Lockwood 2012; Owens et al. 2017), and for predictions of upcoming solar cycles (Svalgaard et al. 2005; Petrovay 2010; Iijima et al. 2017; Upton & Hathaway 2018). Excluding the solar cycle of approximately 11 yr, solar activity has longer-term variations, such as grand minima and secular minima (Solanki et al. 2004; Solanki & Krivova 2004; Usoskin et al. 2007; Clette et al. 2014; Inceoglu et al. 2015; Muscheler et al. 2016; Usoskin 2017). Therefore, it is important to investigate the properties of the sunspot number during the secular minima on the basis of contemporary observations. Certain predictions suggest the possibility of another grand minimum in the near future (e.g., Lockwood 2010; Barnard et al. 2011; Solanki & Krivova 2011; Iijima et al. 2017; Upton & Hathaway 2018). However, we have only two secular minima within the coverage of direct sunspot observations recorded using telescopes for about 400 yr (Hoyt & Schatten 1998a, 1998b; Clette et al. 2014; Clette & Lefèvre 2016; Svalgaard & Schatten 2016; Vaquero et al. 2016), while secular minima and secular maxima are reported in millennial timescale compiled by multiple cosmogenic isotopes from tree-rings and ice cores (Solanki et al. 2004; Usoskin et al. 2007; Inceoglu et al. 2015; Usoskin 2017; Wu et al. 2018).

Further, recent revisions of sunspot number based on historical documents require us to reevaluate the solar activity for a longer timespan (Clette & Lefèvre 2016; Vaquero et al. 2016). Reconsideration of historical documents also suggests that we should seek to new records (Arlt 2008, 2009, 2018; Vaquero 2007; Vaquero & Vázquez 2009; Vaquero et al. 2011; Carrasco et al. 2015; Hayakawa et al. 2018c, 2018b; Carrasco & Vaquero 2016; Denig & McVaugh 2017; Carrasco et al. 2018, 2019b), remove apparent continuous spotless days...
onset has been notably rewritten utilizing multiple methodologies revising, a long-term variation of solar activity was evaluated (Min\text{\textsuperscript{e}}m, 2018; Kataoka et al. 2012; McCracken & Beer 2014) or one of the secular minima in the long-term solar activity (e.g., Usoskin et al. 2015). So far, this “minimum” has been studied, including its amplitude and cyclicity (Schüssler et al. 1997; Sokoloff 2004; Usoskin et al. 2007; Petrovay 2010; Usoskin 2017). After Wolf (1894), the amplitude and cycles of its primary part have been discussed with contemporaneous sunspot observations (Hoyt & Schatten 1992a, 1992b, 1995), and in the auroral reports in Europe (Schröder et al. 2004). Recent studies provide some insights upon the discussions on its onset (Usoskin et al. 2009; Zolotova & Ponyavin 2011) with a revision of the sunspot number (Vaquero et al. 2016; Hayakawa et al. 2018c) and reconstructions of proxies of cosmogenic isotopes (Karoff et al. 2015; Owens et al. 2015). Furthermore, the recovery of sunspot observations for this period is ongoing, for example, in the observations recorded by Jonathan Fisher during 1816–1817 (Denig & McVaugh 2017) or by Franz Hallaschka during 1814–1816 (Carrasco et al. 2018), to improve the reconstruction of sunspot activity. These studies have demonstrated that the Dalton Minimum was possibly considerably different from the Maunder Minimum in terms of the duration and the amplitude of solar cycles (e.g., Miyahara et al. 2004; Usoskin et al. 2007, 2015; Vaquero et al. 2015).

Thaddäus Derfflinger was one of the most active and important long-term observers during the Dalton Minimum (see Figure 18 of Clette et al. 2014; Figure 2 of Svalgaard & Schatten 2016; Figure 1 of Willamo et al. 2017). His sunspot observations were studied by Wolf (1894) long after Derfflinger’s death and were adopted by Hoyt & Schatten (1998a, 1998b) as they were. However, Wolf explicitly admitted that he did not consult the original manuscript but received the information through a letter from Franz Schwab, one of Derfflinger’s successors as the director of the Kremsmünster Observatory (Wolf 1894). Furthermore, the classification method of the sunspot groups seems slightly different from the early modern times to modern time, hence it is subjected to reconsideration (e.g., Svalgaard 2017). Therefore, in this study, we consulted the original manuscript in the Kremsmünster Observatory (see the Appendix), reexamined Derfflinger’s sunspot observations, and reconstructed the time series of the sunspot group number and measured the sunspot positions according to the records in the original manuscripts.

2. Observers: Thaddäus Derfflinger and his Assistants

Thaddäus Derfflinger (Figure 1) was born on 1748 December 19 at Mühlwang near Gmunden, and passed away on 1824 April 18 in Kremsmünster (Fellöcker 1864). He studied theology and mathematics at the University of Salzburg and received his priesthood ordination in Passau. Around 1776, he studied astronomy under Placidus Fixlmillner (1721–1791), the first director of the Kremsmünster Observatory (N48°03', E14°08'). When Fixlmillner passed away in 1791, Derfflinger took over the position of director of the observatory and remained there for 33 yr until his death (Fellöcker 1864). Kremsmünster Observatory is not situated in Germany as reported in Hoyt & Schatten (1998a, 1998b), but in Austria during the Hapsburg Empire (Fellöcker 1864).

While Derfflinger experienced the turmoil during the French invasion under Napoleon in 1800 and 1804–1805 (Fellöcker 1864), he continued his sunspot observations even during the second invasion. He was in regular contact with observatories in Vienna and Prague, including with the contemporary sunspot observer Franz Hallaschka (Fellöcker 1864), whose sunspot records have been recently recovered (Carrasco et al. 2018). During the last two decades of his life, Derfflinger suffered from the degradation of his eyesight and lost his left eyesight in spring 1819 (Fellöcker 1864). The loss is partially because of his long-term sunspot observations. However, he maintained his right eyesight, and supervised the sunspot observations until 1824 March 21, one month before his death (Fellöcker 1864).

Within the monastery, he had two assistants: Benno Waller (1758–1833) and Leander Öttl (1757–1849), two other monks of the confraternity of Benedictines. He had at least three more assistants outside of the monastery: Johann Illinger (1724–1800),
Simon Lettenmayr (father: 1757–1834), and Simon Lettenmayr (son: 1787–1868). Johann Illinger had worked in the observatory since the time of Fixlmillner. Simon Lettenmayr (father) worked not only on the construction and reparation of the monastery buildings, but also as an observational assistant. His son, also named Simon Lettenmayr, accompanied Derflinger during his visit to Prague in 1816 and was advised by Hallaschka to improve and construct observational instruments. He also received basic education in meteorology and astronomy from the teachers of Kremsmünster School and performed magnetic observations under the supervision of the observatory directors: Thaddäus Derflinger, Bonifaz Schwarzenbrunner (1790–1830), and Marian Koller (1792–1866). Eventually, his eyesight considerably degraded and he retired (Fellöcker 1864).

3. Observational Records

Derflinger’s sunspot records are currently preserved in the directorate archives of the Kremsmünster Observatory (see the Appendix). The sunspot drawings have been recorded both in the meteorological logbooks (v. 2–5) and the summary manuscript entitled “Overview of the sunspots which were observed on the observatory of Kremsmünster since 1802 September 26 until 1824 inclusive; then, as of 1848 July 26 (Übersicht der Sonnenmackeln welche auf der Sternwarte zu Kremsmünster seit dem 26. September 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. Juli 1848; see the Appendix). It is inferred that there may have been original daily sunspot drawings besides these manuscripts, made directly at the telescope, as sunspot drawings are cruder in the meteorological logs and more detailed in the summary manuscript.

The summary manuscript (Figure 2(a)) explains in its footnote when and why it was compiled: “Sunspots, from the diaries of Sun noon observations in Kremsmünster, summarized in 1825 February and following years. The drawings illustrate the sunspots like they have been depicted with the inverting lens tube of the azimuthal quadrant of Brander ante meridiem at the observation of the solar altitude” (Figure 2). This footnote shows that the sunspot observations were a byproduct of the regular solar elevation observations to determine local solar noon since 1802.

Accordingly, this summary collected sunspot drawings around midday and was compiled in 1825 February, soon after the death of Derflinger. It seems to have been planned to collect further sunspot drawings after 1825, as shown with the unfilled margin for 1825 without sunspot drawings (summary manuscript, page 7). Furthermore, a sunspot drawing on 1848 July 26 with at least nine sunspot groups was included by an anonymous observer, possibly associated with Augustin Reslhuber, director of Kremsmünster Observatory at the time. On this date, both Schwabe and Shea reported six sunspot groups (Vaquero et al. 2016).

4. Instruments and Telescopes

Since 1802, the Kremsmünster Observatory (Figure 3(a)) monitored the position of the Sun on a regular basis to time the true local noon with the aid of a transportable quadrant. By
measuring various timings of given elevations of the Sun in the morning and in the afternoon, the solar culmination can be computed and the time of true local noon determined. During these measurements, sunspots have been recognized quite frequently and small sunspot sketches have been recorded into the meteorological logbooks (Figure 2(b)).

Several quadrants were used at this observatory to determine local noon (off the meridian). In principle, one of the two mural quadrants mounted in the observation hall (sixth and seventh floor), the one to the south (B), as depicted in a drawing of Fellöcker (1864) seems to have been used. Among them, Derfllinger seemed to use Brander’s 5.5 feet azimuthal quadrant (Wolf 1894) with a micrometer manufactured in Paris (Fellöcker 1864; Figure 3(b)). This instrument has a height of approximately 266 cm, with a telescope with a focal length of approximately 174 cm, the radius of the quarter angular arc is 95 cm, and is mounted on an oaken stand. The instrument was in regular use until 1824 (Fellöcker 1864, p. 12, footnote 10), on the basis of contemporary length unit in Austria (Aldefeld 1838). The summary manuscript (Figure 2(a)) records that this quadrant had an inverting lens, thus, indicating it to be a Keplerian telescope.

5. Sunspot Groups Recorded in Derfllinger’s Manuscript

Examining the summary manuscript and meteorological logbooks, we identified sunspot observations for 487 days. We have counted their group number with the Waldmeier classification (Kiepenheuer 1953) and summarized our result.\textsuperscript{11} The total number is notably less than the number of days with sunspot observation (789 days) in the existing data set (Hoyt & Schatten 1998a, 1998b; Vaquero et al. 2016). This is mainly because we observed that the existing spotless days are likely to be solar elevation observations without sunspot drawings. We eliminated these data.

Wolf (1894) had cited Franz Schwab stating that, On those days when the Sun was observed, without any sunspots being noted, the symbol $\bigcirc$ was applied, which does not mean that the Sun was spotless, but it does indicate that the observer did not notice anything of particular interest on the solar surface; however, sometimes the sketch could have been omitted for lack of time. Nevertheless, Wolf (1894) misleadingly substituted the $\bigcirc$ symbol by the slimmer $0$ to fit it into his published tables. These ‘0’s have been incorporated to Hoyt & Schatten (1998a, 1998b) as spotless days.

As mentioned earlier, these sunspot observations are byproducts of elevation observations. Analogous studies of corresponding solar meridian observations showed that it is not straightforward to reconstruct solar activity from them, as shown in the solar meridian observations by the Royal Observatory of the Spanish Navy (Vaquero & Gallego 2014). Similarly, recent studies have revealed that the solar meridian observations in Bologna (Manfredi 1736) and by Hevelius (1679) had been misinterpreted as spotless days (Vaquero 2007; Clette et al. 2014; Carrasco & Vaquero 2016).

In certain instances, the meteorological logbooks show the solar elevation observations without sunspot drawings while subsequent solar elevation observations show multiple sunspots as observed in Figure 4. Here, while the absence of sunspot drawing on 1818 July 25 had been considered as a spotless day in the existing database (Hoyt & Schatten 1998a, 1998b; Vaquero et al. 2016), this seems unlikely given the fact that a sunspot group (red box in Figure 4) moved from the eastern limb to the disk center and disappeared only on 1818 July 25. Indeed, it is highly unlikely that the sunspot groups disappeared in between for a day within a sequence of observations, while their group numbers and relative locations are almost similar on other observing days. Furthermore, even for the dates of solar meridian observations without sunspot drawings, the summary manuscript occasionally recorded sunspot drawings (e.g., 1816 July 15 and 31). Therefore, we have concluded that Derfllinger’s solar elevation observations without sunspot drawings should not be considered as spotless days, but as an absence of observational data.

Excluding these apparent spotless days, we have also revised seven observational dates, eliminated eight observational dates, and added seven observational dates against the register in the existing data set (Hoyt & Schatten 1998a, 1998b; Vaquero et al. 2016), as per the summary sheet and original meteorological measurements.
logbooks. The summary manuscript records a sunspot drawing on 1824 August 8, whereas the logbook (v. 5, p. 342) does not show any solar elevation observation on that date. This might be because Derfflinger or one of his subordinates may have observed the solar disk on this date outside of the observatory. This incomparable instance indicates that there should have been original drawings made at the telescope from which both the summary sheets and the logbook sketches were copied. Further investigations in the Kremsmünster archives are required in this regard.

Figure 5 shows a time series of revised sunspot group numbers of Derfflinger contextualized on the existing database for the sunspot group number (Vaquero et al. 2016) and additional sunspot observations by Fisher (Denig & McVaug 2017) and Hallaschka (Carrasco et al. 2018).

Figure 4. Consequence of sunspot observations on 1818 July 23–27 in (a) the summary manuscript (page 5) and (b) the logbook (vol. 4, pages 435–436), courtesy of the Kremsmünster Observatory.
In Figure 5, we have incorporated the sunspot group number in Derflinger’s summary manuscript and logbooks as they are and contextualized them upon the existing sunspot group number by contemporary observers. The summary manuscript and logbooks occasionally provide observations with different group number and observations on different days.

As observed in Figure 6, based on our revised sunspot group number series, we have revised Derflinger’s yearly sunspot group number during 1802–1824 in comparison with the number before our revision in the existing data sets (Hoyt & Schatten 1998a, 1998b; Vaquero et al. 2016). Our revision shows a significantly different trend of yearly Derflinger’s sunspot group number (Figure 6) in comparison with that before our revision (Figure 7).

We observed that Derflinger’s trend is much more consistent with the sunspot number (v. 2; Clette et al. 2014; Clette & Lefèvre 2016) than the group sunspot number series (Svalgaard & Schatten 2016; Usoskin et al. 2016) in Cycle 5. However, Derflinger’s data are more consistent with the group sunspot number series than the sunspot number (v. 2; Clette et al. 2014; Clette & Lefèvre 2016) in Cycle 6. The cycle amplitude seems slightly larger in Cycle 5 than in Cycle 6.

6. Measurements of the Sunspot Positions

It is difficult to determine the heliographic coordinates of the sunspots from Derflinger’s drawings as he had not recorded an explicit time for each drawing. There are horizontal and vertical
lines in the drawings, which are supposed to be parallel to the horizon and pointing to the zenith, respectively, as the manuscripts mention that the observations are made with an azimuthal quadrant. The manuscript also states that the images are upside down, i.e., the lower end of the vertical line points to the zenith. An indication of the observing time comes from the logbooks in which the sunspot drawings are inserted above, below, or within the solar elevation timings. Hence, we are using two ways of fixing the position angle of the solar disk to obtain the heliographic coordinates. The first method uses the nearest time of the solar elevation measurements to fix the position angle of the Sun, as it appeared at that time in the sky in a horizontal coordinate system while using an ephemeris provided by the JPL Horizons system.12 These times give subjectively reasonable results for the majority of days. The second method can be employed if the spot(s) were drawn on several days in a row. Assuming the heliographic positions have not changed over the course of the days, the position angles are obtained along with the longitudes and latitudes using Bayesian inference (Arlt et al. 2013). This method is called rotational matching. By utilizing the elevation times, this method was used when a sequence of days with the same spots did not show a consistent progression of the spots. If in such a sequence, only a single day contained an outlier, we adapted the time of observation to a moment when the position angle results in a reasonable progression of the spots. These manually found times typically fall later in the day and indicate that some observations may not have been made in direct connection with the elevation measurements.

We also employed a correction to the clocks, as the solar elevation measurements provide us with the local solar time, i.e., the meridian passage of the Sun. When compared with the solar equation of time, we obtained a correction to the Kremsmünster clocks. The maximum clock correction applied reached $-1.22\ \text{hr}$ on 1804 November 13, after 20 days of bad weather, when the clocks had not been adjusted according to the solar elevation measurements. After the solar minimum starting Cycle 6, the clocks were more precise, and very few observations show deviations of more than 15 minutes.

The butterfly diagram resulting from 2210 sunspot positions of 487 observations is shown in Figure 8. The spot locations during Cycle 5 show a migration of activity toward the equator. There are several spots on the equator, a phenomenon which may be attributed to the low accuracy of the drawings and that we are not plotting group centers (e.g., Figure 9 of Hathaway 2015), but all are individual spot locations. As the groups are apparently plotted in a magnified manner, the individual spots can easily populate the equator, even though the group center is clearly in one of the hemispheres. Cycle 6 looks similar to Cycle 5, while the observational gaps in 1814 and 1815 hide features of the early phase of the cycle. Nevertheless, our butterfly diagram shows the asymmetric appearance of high-latitude spots in the beginning phase of Cycle 6. Figure 8 shows that spots in the northern hemisphere appeared in late 1811, whereas those in the southern hemisphere appeared in mid 1813. Similarly, some high-latitude spots indicate the beginning of Cycle 7 in 1822, whereas from sunspot numbers alone, the cycle minimum is usually placed in early 1823 (Hathaway 2015). Cycle 7 appears to start with spots in the northern hemisphere, but their total number is small. In summary, we conclude that the butterfly diagram is—while slightly asymmetric—generally compatible with its modern shape and that the differences to modern graphs are not significant and attributable to the limited accuracy of the observations.

Error margins of the heliographic positions were obtained in the following way. As the primary unknown quantity in the analysis is the position angle of the solar disk, we assumed a general uncertainty of $\pm10^\circ$ in the position angle. We then

---

12 https://ssd.jpl.nasa.gov/horizons.cgi

13 https://www.kwasan.kyoto-u.ac.jp/~hayakawa/data
7. Conclusions and Outlooks

In this article, we have examined Derfflinger’s sunspot observations on the basis of his original records. Derfflinger’s observations are currently preserved in the directorate archives of the Kremsmünster Observatory as a summary manuscript and meteorological logbooks (v. 2–5; see the Appendix). Derfflinger conducted his sunspot observations from 1802 to 1824 with aids of his assistants, as byproducts of solar elevation observations. Derfflinger used Brander’s 5.5 feet azimuthal quadrant for the observations of sunspots and of the solar elevation.

Examining his original observational records, we have discovered that the existing “spotless days” were contaminations from solar elevation observations without sunspot drawings. Accordingly, these “spotless days” were eliminated, as they do not necessarily mean the absence of sunspots. In contrast, we found evidence that there were sunspots at least in some of those removed data. We have also revised seven observational dates, eliminated eight observational dates, and added seven observational dates against the register in the existing data set (Hoyt & Schatten 1998a, 1998b; Vaquero et al. 2016). We then applied the Waldmeier classification to revise Derfflinger’s group sunspot number. The revised Derfflinger’s trend shows that the amplitude of Cycle 5 is slightly higher than that of Cycle 6. The revised trend seems rather consistent with the sunspot number (v. 2) in Cycle 5, whereas his revised trend in Cycle 6 is more consistent with the group sunspot number series.

We have reconstructed the butterfly diagram on the basis of Derfflinger’s sunspot observations and have filled the existing data gap (see Muñoz-Jaramillo & Vaquero 2019). The reconstructed butterfly diagram demonstrates no significant asymmetry of sunspot distributions like that of the Maunder Minimum (Ribes & Nesme-Ribes 1993). We observed considerable sunspots near the solar equator, probably due to the limited accuracy of Derfflinger’s sunspot observations.

Our revision shows that Derfflinger’s sunspot cycles during the Dalton Minimum have a slightly higher amplitude of the solar activity than previously considered. The data gap of the butterfly diagram in this period has been filled and does not show extremely asymmetric sunspot distributions like those of the Maunder Minimum. Our reconstruction shows that the Dalton Minimum was significantly different from the Maunder Minimum, either in terms of cycle amplitude (see Usoskin et al. 2015), its duration (see Miyahara et al. 2004; Vaquero et al. 2015), or its more symmetric butterfly diagram (see Ribes & Nesme-Ribes 1993).

Primarily, the reconstructed cycles during the Dalton Minimum were approximately 11 yr (≈12 yr), while the period during the Maunder Minimum was probably either considerably shorter (Vaquero et al. 2015) or longer (Miyahara et al. 2004) than 11 yr. A peculiarity of the early Dalton Minimum was a “hiccup” in the cycle period. This may have been either a very long cycle of approximately 15 yr duration (Hathaway 2015) or a short cycle followed by a very weak one of, respectively, a little less than 9 yr and more than 7 yr (Usoskin et al. 2009). That period falls before Derfflinger’s observations.

Our study hints to an understanding of the Dalton Minimum as not toward a grand minimum characterized with extremely weak or even collapsed solar dynamo cycles, but more toward a secular minimum in the long-term solar activity slightly longer cycles with low activity. This notion is more consistent with a solar dynamo that continued to produce a reasonable number of sunspots during the Dalton Minimum. Potential deviations from the average cycle length are probably determined by quantities which are difficult to
access in historical observations, such as the meridional circulation, stochastic variations in the convective patterns, or the internal rise time of magnetic flux to the solar surface (e.g. Charbonneau 2013, Chapter 4; Fournier et al. 2018).

Nevertheless, it has been determined that Derfflinger did not record spotless days during his observations and the cycle amplitudes during the Dalton Minimum may be revised slightly downward in future. We are required to carefully investigate and revise the data of other contemporary sunspot observers during the Dalton Minimum, revise the actual group number, and define the actual spotless days. Additionally, spot areas are to be studied further owing to their seemingly exaggerated size as observed in other historical observations using aerial imaging method (see e.g., Fujiyama et al. 2019; Karachik et al. 2019). Further document research on the Dalton Minimum will improve our knowledge of solar activity during the secular minima or the suppressed solar cycles.

We thank Kremsmünster Observatory for permitting access to Derfflinger’s manuscripts and for the reproduction of some observational records as well as preserving these records. H.H. thanks F. Clette and S. Toriumi for their helpful comments. This research has been conducted with aids of KAKENHI grant No. 15H05812 (PI: K. Kusano), JP15H05816 (PI: S. Yoden), and JP17H06954 (PI: H. Hayakawa), as well as the Austrian Science Foundation (FWF) project P 31088 (PI: U. Fösche) and the Deutsche Forschungsgemeinschaft grant No. AR355. This work has been partly merited from participation to the International Team 417 “Recalibration of the Sunspot Number Series.”

Appendix

Historical Sources

Summary Manuscript: Übersicht der Sonnenmackeln, welche auf der Sternwarte zu Kremsmünster seit dem 26. September 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. Juli 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. Juli 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. Juli 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. Juli 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. Juli 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. Juli 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. Juli 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. July 1808 – 1813. In 1802 beobachtet wurden, bis 19

Appendix

Historical Sources

Summary Manuscript: Übersicht der Sonnenmackeln, welche auf der Sternwarte zu Kremsmünster seit dem 26. September 1802 beobachtet wurden, bis 1824 inclusive; dann vom 26. Juli 1848. MS, Direktions-Archiv der Sternwarte Kremsmünster. Logbook (v.2): Meteorologische Beobachtungen zu Kremsmünster 1801–1807, II. Bd. MS, Direktions-Archiv der Sternwarte Kremsmünster. Logbook (v.3): Meteorologische Beobachtungen zu Kremsmünster 1808–1813, III. Bd. MS, Direktions-Archiv der Sternwarte Kremsmünster. Logbook (v.4): Meteorologische Beobachtungen zu Kremsmünster 1814–19, IV. Bd. MS, Direktions-Archiv der Sternwarte Kremsmünster. Logbook (v.5): Meteorologische Beobachtungen zu Kremsmünster 1820–25, V. Bd. MS, Direktions-Archiv der Sternwarte Kremsmünster.

ORCID iDs

Hisashi Hayakawa @ https://orcid.org/0000-0001-5370-3365 Bruno P. Besser @ https://orcid.org/0000-0002-8536-422X Shinsuke Imada @ https://orcid.org/0000-0001-7891-3916 Philippe-A. Boudrin @ https://orcid.org/0000-0002-6793-601X

References

Alfeld, C. L. W. 1838, Die Maafle und Gewichte der Deutschen Zoll-Vereins-Staaten (Stuttgart: Cotta) (in German)
Arlt, R. 2008, SoPh, 247, 399
