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Sunspot Observations at the Eimmart Observatory and in Its Neighborhood during the Late Maunder Minimum (1681–1718)

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Abstract

The Maunder Minimum (1645–1715; hereafter MM) is generally considered as the only grand minimum in the chronological coverage of telescopic sunspot observations. Characterized by scarce sunspot occurrences and their asymmetric concentrations in the southern solar hemisphere, the MM has frequently been associated with a special state of solar dynamo activity. As such, it is important to analyze contemporary observational records and improve our understanding of this peculiar interval, whereas the original records are frequently preserved in historical archives and can be difficult to access. In this study, we consult historical archives in the National Library of Russia, St. Petersburg, and analyze a series of sunspot observations conducted at the Eimmart Observatory from 1681 to 1709, which is the second-richest sunspot data set produced during the MM, following La Hire's series, among existing data sets. We have further extended our analyses to neighboring observations to extend our investigations up to 1718. We first analyze source documents and descriptions of observational instruments. Our analyses have significantly revised the existing data set, removed contaminations, and updated and labeled them as Eimmart Observatory (78 days), Altdorf Observatory (4 days), Hoffmann (22 days), and Wideburg (25 days). The revisions have updated the temporal coverage of the contemporary sunspot observations from 73.4% to 66.9% from 1677 to 1709. We have also derived the positions of the observed sunspot groups in comparison with contemporary observations. Our results indicate hemispheric asymmetry in the MM and recovery of sunspot groups in both hemispheres after 1716, supporting the common paradigm of the MM.

Unified Astronomy Thesaurus concepts: Maunder minimum (1015); Sunspot cycle (1650); Sunspot groups (1651); Sunspot number (1652); Solar activity (1475); Solar-terrestrial interactions (1473)

1. Introduction

Solar variability has been directly monitored based on the number of sunspot groups and individual sunspots since 1610. This time series has formed one of the longest ongoing scientific experiments in human history (Owens 2013; Clette et al. 2014; Arlt & Vaquero 2020). Since then, the numbers and distributions of observed sunspot groups have formed relatively symmetric cycles approximately every 11 yr in both solar hemispheres, in harmony with the variable morphology of the solar coronal streamers (Hathaway 2015; Owens et al. 2017; Muñoz-Jaramillo & Vaquero 2019; Arlt & Vaquero 2020). However, their reconstructions before 1900 are more challenging (Clette et al. 2014; Muñoz-Jaramillo & Vaquero 2019) and hence have experienced active recalibrations using variable sources and multiple methods (Clette & Lefèvre 2016; Lockwood et al. 2016; Svalgaard & Schatten 2016; Usoskin et al. 2016; Cliver 2017; Chatzistergos et al. 2017).

Among the entire time series of the observed solar cycles, the Maunder Minimum (MM) during 1645–1715 has been considered unique, with extremely suppressed sunspot activity. Indeed, in this epoch, reported sunspots were extremely scarce, their occurrences were mostly concentrated in the southern solar hemisphere, and coronal streamers were apparently missing (e.g., Eddy 1976; Ribes & Nesme-Ribes 1993; Hoyt & Schatten 1998a; Sokoloff 2004; Nagovitsyn et al. 2010; Riley et al. 2015; Usoskin et al. 2015; Hayakawa et al. 2021), in contrast with other solar cycles, including even the Dalton Minimum (Muñoz-Jaramillo & Vaquero 2019; Hayakawa et al. 2020a, 2020b). As such, the MM has been considered the only grand minimum representing a special state of the solar dynamo activity within the coverage of direct solar observations (Usoskin et al. 2015; Cameron et al. 2017; Charbonneau 2020) and is considered the standard reference for other grand minima detected in the multiproxy reconstructions in natural archives (e.g., Usoskin et al. 2007; Inceoglu et al. 2015; Usoskin 2017).

The MM was initially characterized by an excessive number of spotless days determined from fairly regular sunspot observations (>90% spotless days) by Hoyt & Schatten (1998a, 1998b, hereafter HS98). However, close inspections have shown that spotless days have been frequently derived from philological misinterpretations or contaminations from general statements on an absence of sunspots for some period or solar altitude observations (Vaquero 2007; Clette et al. 2014;

Hayakawa et al. 2020c). Recent analyses of historical observations indicate that the sunspot group numbers during and around the MM have indeed suffered from such contaminations (Vaquero et al. 2011; Carrasco et al. 2015; Carrasco & Vaquero 2016). These revisions have been compiled in Vaquero et al. (2016, hereafter V+16), and the MM active day fraction has been modified slightly upward, whereas its actual amplitude remains a topic of intense debate (Usoskin et al. 2015; Vaquero et al. 2015a; Svalgaard & Schatten 2016), such that analyses and revisions of historical observations during the MM continue to date (Hayakawa et al. 2018; Carrasco et al. 2019a, 2019b, 2020).

Another curious characteristic of the MM involves its sunspot distributions, which were concentrated in the southern solar hemisphere (Spörer 1889; Ribes & Nesme-Ribes 1993; Sokoloff 2004; Nagovitsyn et al. 2010; Arlt & Vaquero 2020), whereas this trend was probably not shared with its onset or aftermath (Carrasco et al. 2019b; Arlt & Vaquero 2020; Hayakawa et al. 2020c). This difference highlights the peculiarity of the MM in comparison with other epochs, including the Dalton Minimum (Muñoz-Jaramillo & Vaquero 2019; Hayakawa et al. 2020a, 2020b). This has been associated with a special state of the solar dynamo during grand minima (Cameron et al. 2017; Charbonneau 2020). As such, reconstructions of sunspot positions during the MM and afterward are of particular importance to improve knowledge of grand minima.

In this context, the historical observations at the Eimmart Observatory are of particular interest, as they document one of the longest and richest series during the MM. These observations have been acquired by Hoyt & Schatten (1995, 1996, 1998a, 1998b) from St. Petersburg's State Library. According to the revised data set (V+16), "G. C. Eimmart" conducted observations during 1677–1702 and was the second most active sunspot observer (only surpassed by La Hire) before the end of the MM. From the same archives, sunspot records by "M. C. Eimmart" and "J. H. Muller" have also been reported from 1703–1704 and 1705–1709 (HS98; V+16), respectively. "J. H. Muller" was also associated with another series in 1716–1718. However, specific details by these observers have only briefly been mentioned in the online bibliography of HS98, and their manuscripts have been virtually inaccessible to the solar community, except for sunspot group numbers. In this study, we have located their original manuscripts with exact shelf marks, and detailed the profiles of these observers and their source documentation. Their observational instruments are described, and we have analyzed actual sunspot group numbers after removing contaminations and reconstructed the positions of the reported sunspot groups.

2. Observational Records and Observers

HS98 derived the data of these three observers at the Eimmart Observatory (G. C. Eimmart, Maria Clara Eimmart, and J. H. Muller) from the "Eimmart Papers at the St. Petersburg Library," emphasizing that their observations were not acquired by Rudolf Wolf (e.g., Wolf 1850a, 1850b). Our investigation has identified their original observational records in the Eimmart Collection at the Manuscript Department of the National Library of Russia (MS OR RNB, fond 998).[11] Three observers have been confirmed here: Georg Christoph Eimmart (hereafter GCE; 1638–1705), Maria Clara Eimmart (hereafter MCE; 1676–1707), and Johann Heinrich Müller (hereafter JHM; 1671–1731), based on the manuscript catalog in RNB (RNB 1958, p. 76). Our identifications are confirmed through the user lists (Лист использования) of these manuscripts, where Douglas Hoyt's consultations are explicitly recorded.

GCE was a founder and the first director of the Eimmart Observatory. He received an education in painting and engraving from his family and studied mathematics, astronomy, and jurisprudence at the University of Jena in Germany. Moving to Nürnberg (near Fleischbrücke), GCE began to record his solar altitude measurements on 1677 September 5. In fall 1678, he established his private observatory, the Eimmart Observatory, at Vestnertor Bastion of Nürnberg Castle (N49°27, E11°05; Figure 1), where regular observations were carried out until 1751 (Müller 1713; Gaab 2005, 2010; Hockey 2014, p. 647). His daughter, MCE, assisted with his astronomical observations and produced a number of astronomical drawings, such as the Moon in various phases and planets, comets, and total solar eclipses, and significantly contributed to her father's work with her reputable illustrations (e.g., Eimmart 1701). She married JHM but died young giving birth in 1707 (Gaab 2005, 2010; Bernardi 2016, pp. 97–101; Hayakawa et al. 2021). JHM was from Wöhrd, near Nürnberg, studied astronomy under GCE, and assisted with the Eimmart family's astronomical observations. He was appointed as director of this observatory after GCE passed away in 1705, at which time the city government of Nürnberg bought it (Bernardi 2016, p. 99). He also became a Gymnasium professor of physics at Nürnberg. In 1710, he became a professor at Altdorf, set up a new observatory there (Müller 1713; Gaab 2005, 2011), and continued his sunspot observations (Müller 1723).

Their records are generally in the form of astronomical logbooks, including solar observations such as those for solar altitude, solar diameter, and sunspots. GCE's observations are recorded from 1677 to 1702 in t. 48 (1677–1683), t. 15 (1683–1684), t. 16 (1684), and t. 17–34 (1685–1702). Note that a manuscript copy of t. 48 is also available at the University of Erlangen–Nürnberg Library as MS 848. This copy was probably made from t. 48 by Johann Leonhard Späth at Altdorf. In particular, from 1685 to 1702, each volume of these logbooks covers 1 yr and systematically recorded solar events near their beginning folia. MCE's observations were recorded from 1703 to 1704 in the early half of t. 35 in a similar format, whereas both GCE (t. 35, l. 36) and JHM (t. 35, l. 1-6b) partially contributed to this volume (RNB 1958). JHM's observations are recorded from 1705 to 1709 in the latter half of t. 35 and another Latin pamphlet (t. 36) involving various astronomical observations, including solar observations. Some of JHM's observations at Altdorf were published in Müller (1723) and also acquired by Wolf (1850a, p. 50). Both MCE and JHM received pamphlets from Johann Heinrich Hoffmann (hereafter JHH; 1669–1716) involving sunspot observations made in 1703.

After JHM's death, these manuscripts were passed to his wife Apollonia Lechner (d. 1751) and her late husband Johann Albrecht Spies (d. 1766), then to Wolfgang Albrecht Spies (d. 1788). After W. A. Spies' death, his estate, including these manuscripts, was bought by Franz Huberti (d. 1789), a Jesuit professor of mathematics and astronomy at Würzburg. These manuscripts were then sent to a Jesuit monastery at Polotsk in 1786 May. After expulsion of the Jesuits from Polotsk in 1821,

[11] Hereafter, we abbreviate fond (фонд, collection), tom (том, volume), and list (лист, folio) as f., t., and l.

Figure 1. Eimmart Observatory at Vestnertor Bastion of Nürnberg Castle, depicted by Johann Adam Delsenbach in 1716 (Stadtbibliothek im Bildungscampus Nürnberg: Stoer. 1257, Bl. 37). Courtesy of Stadtbibliothek im Bildungscampus Nürnberg.

these manuscripts were moved to their present location in St. Petersburg (Gaab 2005, pp. 13–14).

3. Observational Instruments

The instruments used at the Eimmart Observatory for each sunspot observation have not been described in significant detail, whereas contemporary descriptions of these instruments provide some general indications. The precision of the solar altitude measurements indicates that GCE began to use larger quadrants on 1680 June 4 (Gaab 2005, p. 18). The first description of observational instruments at the Eimmart Observatory is found in Christoph Jakob Glaser's pamphlet (Glaser 1691). Glaser worked as an assistant at the Eimmart Observatory from 1680 to 1683. A smaller telescope and instrument for solar observation are mentioned as Machina Helioscopica in Glaser's graphical summary of the observational instruments (Figure 2(a); Glaser 1691). Accordingly, the Eimmart Observatory hosted two dark chambers (*camerae obscurae*), and one chamber was specifically dedicated to the observations of sunspots and solar eclipses. A helioscope weakened the sunlight, and a Machina Helioscopica was used to project the solar image onto a plate. This telescope was described as a "small helioscopium" in 1751 (Zinner 1956, pp. 301–303; Forbes 1970).

Later, Rost (1718), who has used the instruments at the Eimmart Observatory, provided further details on the helioscope (Figure 2(b)). Here he described this Machina Helioscopica in a dark chamber used for observations of solar eclipses and sunspots. This instrument was used in combination with a telescope measuring $\geqslant 2$ feet in length (≈ 58 cm; e.g., Sandweg 1982, p. 105), and a clean, plain-cut green glass was placed in front of the telescope eyepiece to allow observations without the projection apparatus (Rost 1718, pp. 293 and 368). Importantly, JHM clarified that no new instruments were purchased after GCE's death in 1705, and that he himself strived to keep the old instruments working (Stadtarchiv Nürnberg: MS B1/II Nr. 1883). In fact, Glaser and Rost described almost the same instruments, despite the approximately three-decade chronological difference between their descriptions. Unfortunately, no information on the aperture of the telescopes used in the Eimmart Observatory has been found to date.

As such, no major changes in the observational instruments are expected to have occurred among the instruments used by the observers at the Eimmart Observatory. Rost described these observational instruments as follows: "This tool, pictured in Figure 27 [NB see our Figure 2(b)], the blessed Mr. Eimmart has used at occasion of different solar eclipses and the observation of sunspots at the local observatory [NB Eimmart Observatory]. It is from steel metal and looks like a common speaking tube ABC; however, it is not open on the bottom but covered at the base BOCN. If desirable, one can on one side of the mentioned bottom furnish it with a screw thread to open and close it at demand. At the upper aperture A, one inserts vertically a telescope GH of size two, three or more feet in length, which has to be stretched more than usual and extended [to achieve focus in projection as compared to looking through the telescope]. One hangs it, together with the extended tinny cylinders LM or LK onto a movable column Figure 26 and holds the upper part A or G parallel against the Sun, that the solar disk appears in sufficient size and well-focused at the Circulo Observatorio, the inner part of the base BNCO, on a white sheet of paper, which one can see through the opening aperture of the instrument F. One draws from the center D the solar disk on to the paper and also out of D six concentric circles in the same fashion: in this way the solar disk is

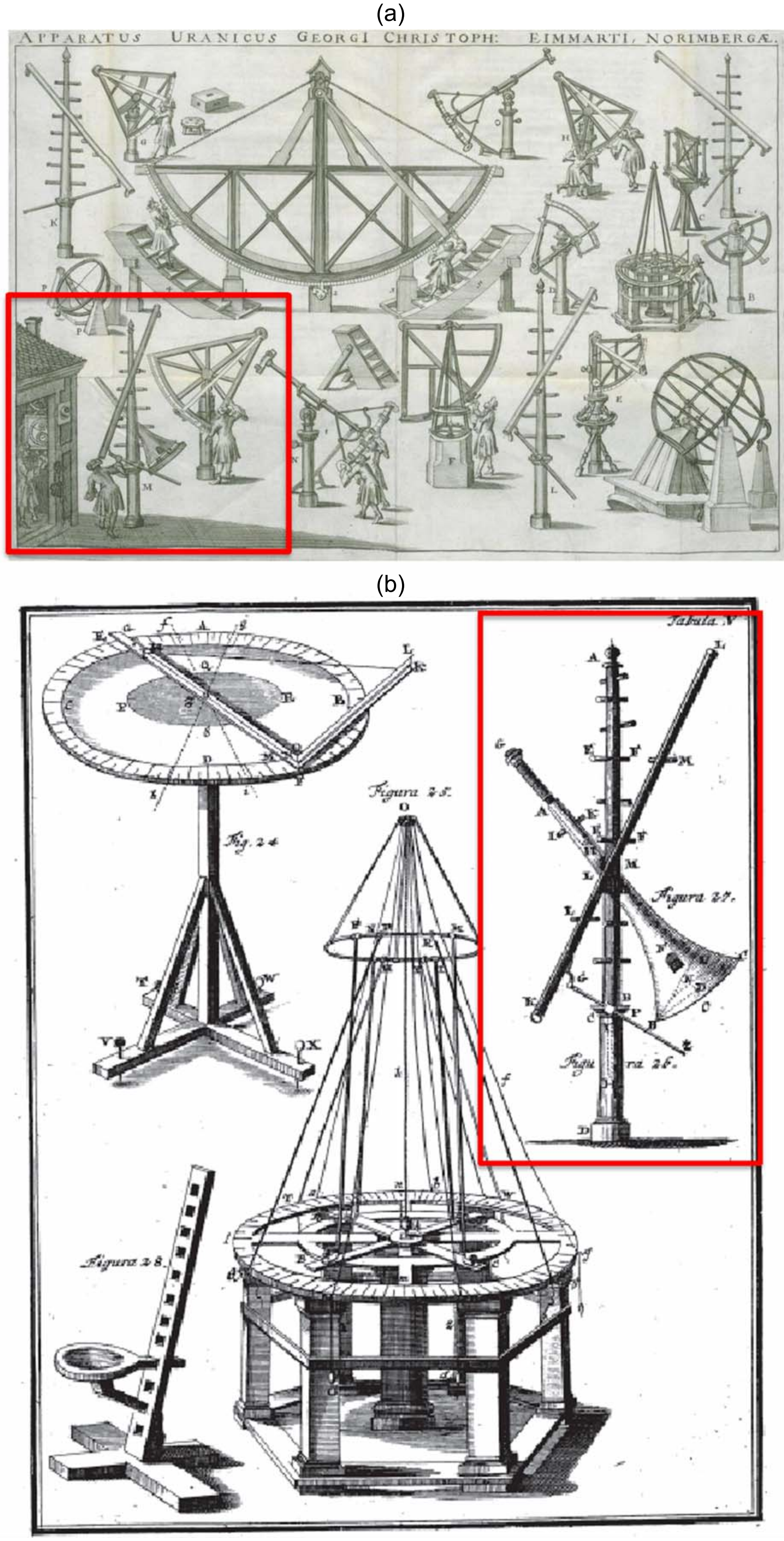

Figure 2. (a) Observational instruments used at the Eimmart Observatory as shown in (a) Glaser (1691) and (b) Rost (1718). In Glaser's diagram (a), the Machina Helioscopica is depicted as instrument M and highlighted by a red square; in Rost's diagram (b), this helioscope is depicted in his Figures 26 and 27.

(a) (b)

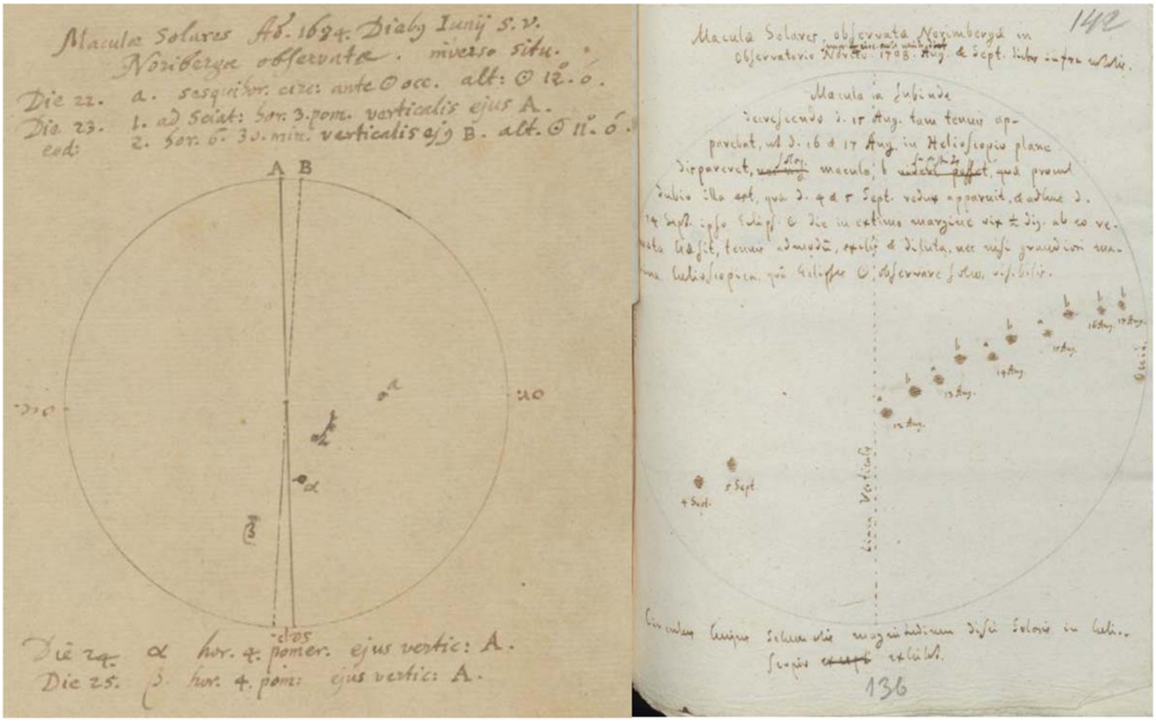

Figure 3. Examples of sunspot drawings in the Eimmart collection. (a) GCE's sunspot drawings on 1684 June 22–25 in the Julian calendar (1684 July 2–5 in the Gregorian calendar; MS OR RNB, f. 998, t. 16, l.1(b)) and (b) JHM's sunspot drawings on 1708 August 12–17 and September 4–5 in the Gregorian calendar (MS OR RNB, f. 998, t. 36, l. 136). They are reproduced here with courtesy of the National Library of Russia.

subdivided into twelve parts or inches. However, one can, if the disk is large, through more subtle or dashed lines, draw more circles, and therefore divide into the half inches or even smaller parts" (Rost 1718, p. 359). Meanwhile, some caution is necessary regarding whether the solar images were always projected, as Rost (1727, p. 289) stated that "not everyone should be able to get it right" when using the Machina Helioscopia.

4. Sunspot Group Number

We analyzed the observational logbooks of GCE, MCE, and JHM, as well as JHH's two pamphlets in the Eimmart Collection (MS OR RNB, f. 998), JHM's summary of his observations in Altdorf Observatory (Müller 1723), and Wideburg's contemporary records (Wideburg 1709), and counted the sunspot groups based on the Waldmeier classification (Kiepenheuer 1953). Within these records, we have identified 7 days of sunspot observations in 1684 as well as 33 days of solar observations within general descriptions of a spotless Sun, in GCE's logbooks during 1681–1682 (MS OR RNB, f. 998, t. 15–34, and 48); 5 days in MCE's logbook in 1703 (MS OR RNB, f. 998, t. 35); 66 days in JHM's logbooks during 1705–1709 (MS OR RNB, f. 998, t. 35–36); 4 days in JHM's observations at Altdorf during 1716–1718 (Müller 1723); and 22 days in JHH's pamphlets in 1703 (t. 3 and 35). Some examples are shown in Figure 3. The observations before 1700 have been revised from the Julian calendar to the Gregorian calendar, as the Improved Imperial Calendar has been enforced since 1700 in Nürnberg (Von Aufgebauer 1969). Our revisions have dramatically reduced the number of observational days by GCE (2325 days by V+16), MCE (141 days), and JHM (80 days) and slightly increased those of JHM at Altdorf (3 days) in comparison with V+16. The number of observation days by JHH (22 days) analyzed in our work is apparently the same as V+16; we removed 1 day (1703 June 26) and added 1 day (1703 July 16).

This significant data removal occurred mainly because of contamination of other observations incorporated into the existing data sets. As shown in Figure 4, the majority of the solar observations by the Eimmart Observatory were not sunspot observations but rather solar altitude measurements instead. Moreover, MCE recorded a solar altitude measurement on July 5 but no sunspot observation, a sunspot observation on July 9 without a solar altitude measurement, and both a solar altitude measurement and a sunspot observation on July 14 (Figure 4(b)). This example explicitly demonstrates that the solar altitude measurements and sunspot observations were made independently of one another at the Eimmart Observatory. On the other hand, it appears that the existing databases (HS98; V+16) have globally interpreted them as spotless days based on GCE's (e.g., Figure 3(a)) and MCE's (e.g., Figure 3(b)) logbooks but have exceptionally interpreted the solar altitude observations from 1703 May to July as active days. This exceptional interval partially coincides with actual sunspot observations in MCE's logbook and JHH's pamphlets. Likewise, the existing data sets have interpreted dates with solar altitude observations without explicit sunspot descriptions/drawings as having been taken on apparently spotless days in JHM's logbook in 1705 (Figure 4(c)). It has already been shown that solar altitude observations without sunspot drawings do not necessarily indicate spotless days, and such misinterpretations have frequently affected the reconstructions of sunspot group numbers (Vaquero 2007; Clette et al. 2014; Vaquero & Gallego 2014; Hayakawa et al. 2020a). Therefore, it should not be assumed that spotless conditions were present when only solar altitude observations were recorded. These

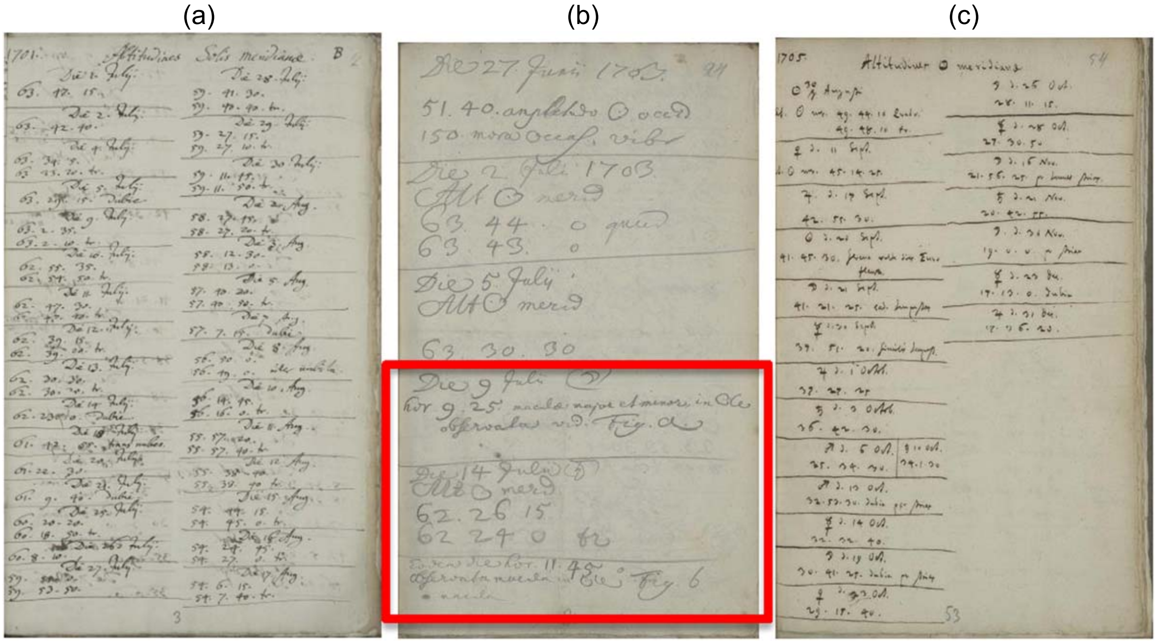

Figure 4. Examples of solar altitude observations from logbooks of the Eimmart Observatory. (a) GCE from 1701 July 1–August 17 (MS OR RNB, f. 998, t. 33, l. 3), which HS98 interpreted as spotless days; (b) MCE from 1703 June 27–July 14 (MS OR RNB, f. 998, t. 35, l. 24), which HS98 interpreted as active days with some dating errors but only containing sunspot descriptions on July 9 and 14, as indicated by the red square; and (c) JHM on 1703 August 30–December 31 (MS OR RNB, f. 998, t. 35, l. 53), which HS98 interpreted as spotless days except for dates accompanied by sunspot drawings. They are reproduced here with permission from the National Library of Russia.

"data" should be removed from discussions of the solar activity at that time.

On the other hand, observers at the Eimmart Observatory occasionally recorded spotless days in textual form. GCE recorded general statements on the absence of sunspots between the beginning of 1681 and the end of August and then until 1682 July 10 in the Julian calendar (MS OR RNB, f. 998, t. 48, l. 163). In this interval, we have identified 33 days of solar observations based on solar altitude and/or diameter (MS OR RNB, f. 998, t. 48, l. 6–6b, and 157–158b). Accompanied by general descriptions of the spotless Sun, these observational dates are contrasted with the other dates when only solar altitude observations were recorded without any mention of either the presence or absence of sunspots on the solar disk. Therefore, on this basis, these dates may be interpreted as spotless days, although this is rather speculative and should be cautiously treated in future discussions. On the other hand, there are a number of datable spotless days, especially in JHM's logbooks and JHH's pamphlets. In addition to several reports of spotless days immediately after active days, JHM systematically recorded the absence and presence of spotless days in 1709 (MS OR RNB, f. 998, t. 36, l. 151–151b; Figure 5) and conveyed details regarding the extremely low active day fraction in 1709, even in comparison with the modern deep minima or the Dalton Minimum.

Furthermore, we have modified their dating based on the original manuscripts. GCE's observations in 1684 have been modified to the Gregorian calendar, as GCE actually followed the Julian calendar at that time. Two of MCE's observations in 1703 have been modified (i.e., 1703 July 14 and 16) from the existing dates in HS98 and V+16. For JHM's observations, we added one spotless day (1706 December 21) and one active day (1709 December 5) and corrected one date (1709 November 17).

Apart from the archival reports of the Eimmart Observatory, MCE and JHM inserted two handwritten pamphlets from JHH at the Berlin Observatory: *Macula in Sole Observata in Berolini anno 1703 diebus Maij Junij & Julij* (Spot in the Sun observed in Berlin in 1703 May, June, and July), with observations on 1703 May 26–July 16 (MS OR RNB, f. 998, t. 3, l. 422–424b and t. 35, l. 43–43b). Among them, HS98 appears to have only consulted t. 35, based on what is recorded in the user lists (Листиспользования). In comparison to HS98, V+16 declared no revisions on these data. JHH's observations almost coincide with the HS98 data, whereas we added one observation on 1703 July 16, removed one observation on 1703 June 3 (a cloudy day), and revised the value of the JHH observation on 30 June 1703 (to a spotless day). The pamphlet in t. 3 is especially valuable (MS OR RNB, f. 998, t. 3, l. 422–424b), involving sunspot tracks illustrated on three whole-disk drawings, whereas this manuscript was overlooked in HS98. Additionally, JHM's observations after his move to Altdorf (N48°33, E12°06) are summarized in Müller (1723). Here, in comparison to HS98 and V+16, we have revised one observational date to 1718 March 2 and added one observation on 1718 March 28.

JHM's late observations in 1708–1709 chronologically overlap with Wideburg's sunspot observations in 1708–1709 (Wideburg 1709; see also Wolf 1861, pp. 96–97), whose data have been partially registered as "Wiedenburg" in the existing data sets (HS98; V+16). We have derived Wideburg's observations from August 13 to 17 and 1708 September 3 to 11 (Wideburg 1709, Figure 1); 1708 November 19 and 21 (Wideburg 1709, Figure 2); 1708 November 30 and December 1 (Wideburg 1709, Figure 4); and 1709 January 7, 9–10, and 31 and February 5 (Wideburg 1709, Figure 3), as well as one spotless day on 1709 August 18 (Wideburg 1709, pp. 11–12) and one active day (one group) on 1708 November 26 (Wideburg 1709, p. 13). While the existing databases (HS98

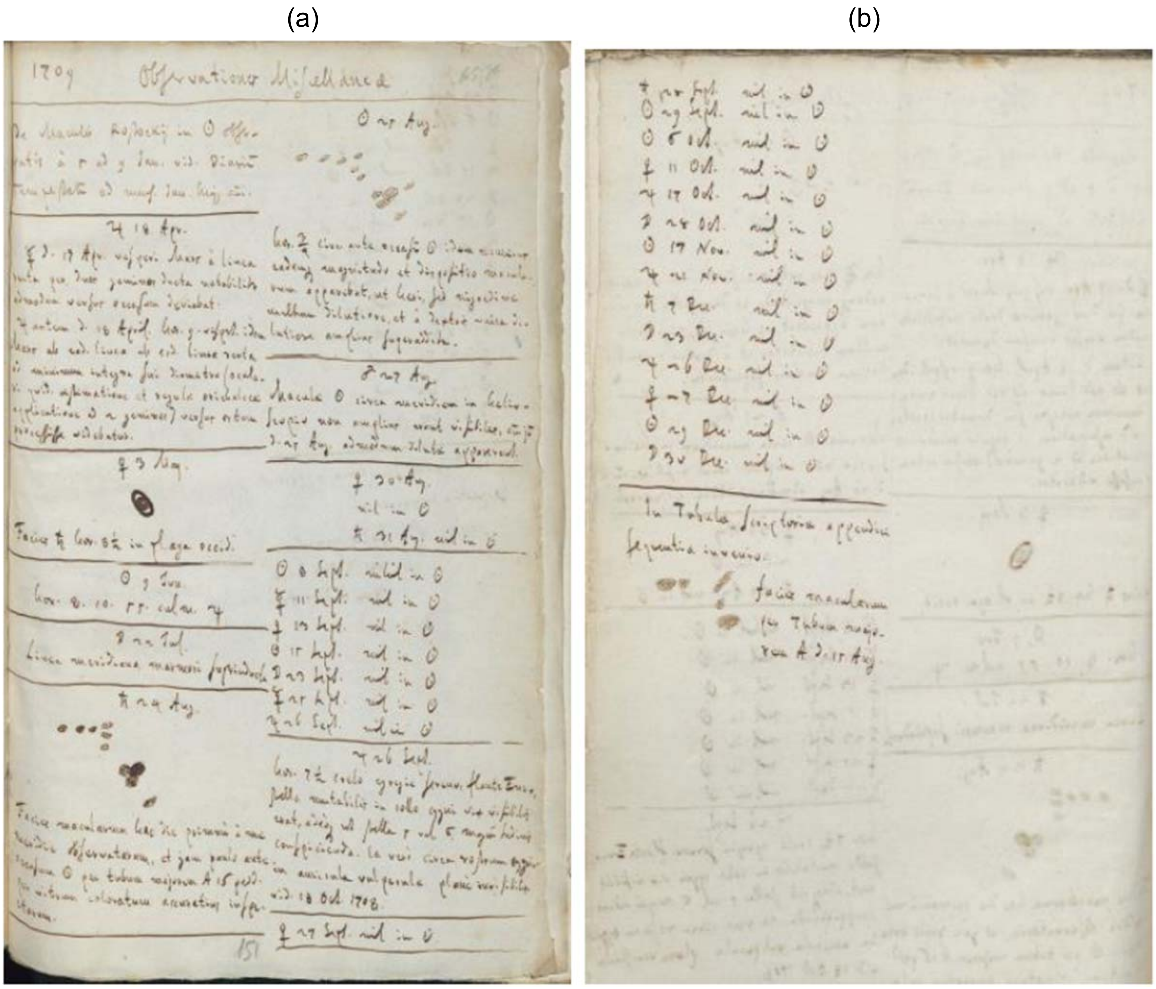

Figure 5. Descriptions of spotless days in JHM's logbook (MS OR RNB, f. 998, t. 36, l. 151–151b). They are reproduced here with permission from the National Library of Russia.

and V+16) have interpreted some observations as two groups, we consider that these observations involve at best a single group. Additionally, we have removed Wideburg's reported continuous spotless days during 1708 January 16–August 10 and on August 21 because we consider these dates undocumented in the original documents: Wideburg (1709) and Wolf (1861, pp. 96–97). These dates were probably misinterpreted from descriptions by Paris observers in Spörer (1889).

The sunspot group numbers recorded at the Eimmart Observatory before and after our revision are summarized in Figure 6 (see also Table 1), in comparison with the existing data sets (V+16). Here we have removed existing data for Rost and Alischer's sunspot group numbers owing to probable overestimations (see, e.g., Rost 1720). Figure 6 explicitly highlights the removal of the majority of the sunspot group numbers by GCE (1677–1702) and MCE (1703–1704) in the existing databases (V+16), owing to contamination arising from observations made for different purposes. Our revision indicates that observational coverage will be revised to 1684 (or 1681–1684 with general statements) for GCE, 1703 for MCE, 1703 for JHH, 1705–1709 for JHM at Nürnberg, and 1716–1718 for JHM at Altdorf. We highlight that the temporal coverage from V+16 for the period 1677–1709 is 73.4%, taking into account all observers. Applying our revision to V+16, the temporal coverage decreases to 66.9%. This decrease is more significant during the period 1685–1702, where the temporal coverage from V+16 for that period is 71.4%, and it is 61.5% after applying our revision.

Except for JHM, the other observers at the Eimmart Observatory and their neighbors (i.e., GCE in 1684, MCE in 1703, and JHH in 1703) recorded sunspot group numbers as being either 0 or 1. On the other hand, JHM recorded multiple sunspot groups after moving to Altdorf (1716–1718), whereas he reported the number as either 0 or 1 during his observations at Nürnberg (1705–1709). This is consistent with the expected larger solar amplitude of solar cycle −3 compared to solar cycle −4 in reconstructions of the group sunspot numbers (e.g., Svalgaard & Schatten 2016) and those of the relative sunspot numbers in the Sunspot Index and Long-term Solar Observations (SILSO) database (Clette & Lefèvre 2016). Moreover, this trend agrees with the observed return of the coronal streamers between 1706 and 1715, namely, between solar cycles −4 and −3 (Eddy 1976; Riley et al. 2015; Hayakawa et al. 2020b).

5. Sunspot Positions

The sunspot positions recorded in the Eimmart Collection were measured based on the original manuscripts. As shown in Figures 3 and 7(a), sunspots are frequently recorded in daily sequences in the same whole-disk drawings, whereas insufficient descriptions make it challenging to obtain the exact solar

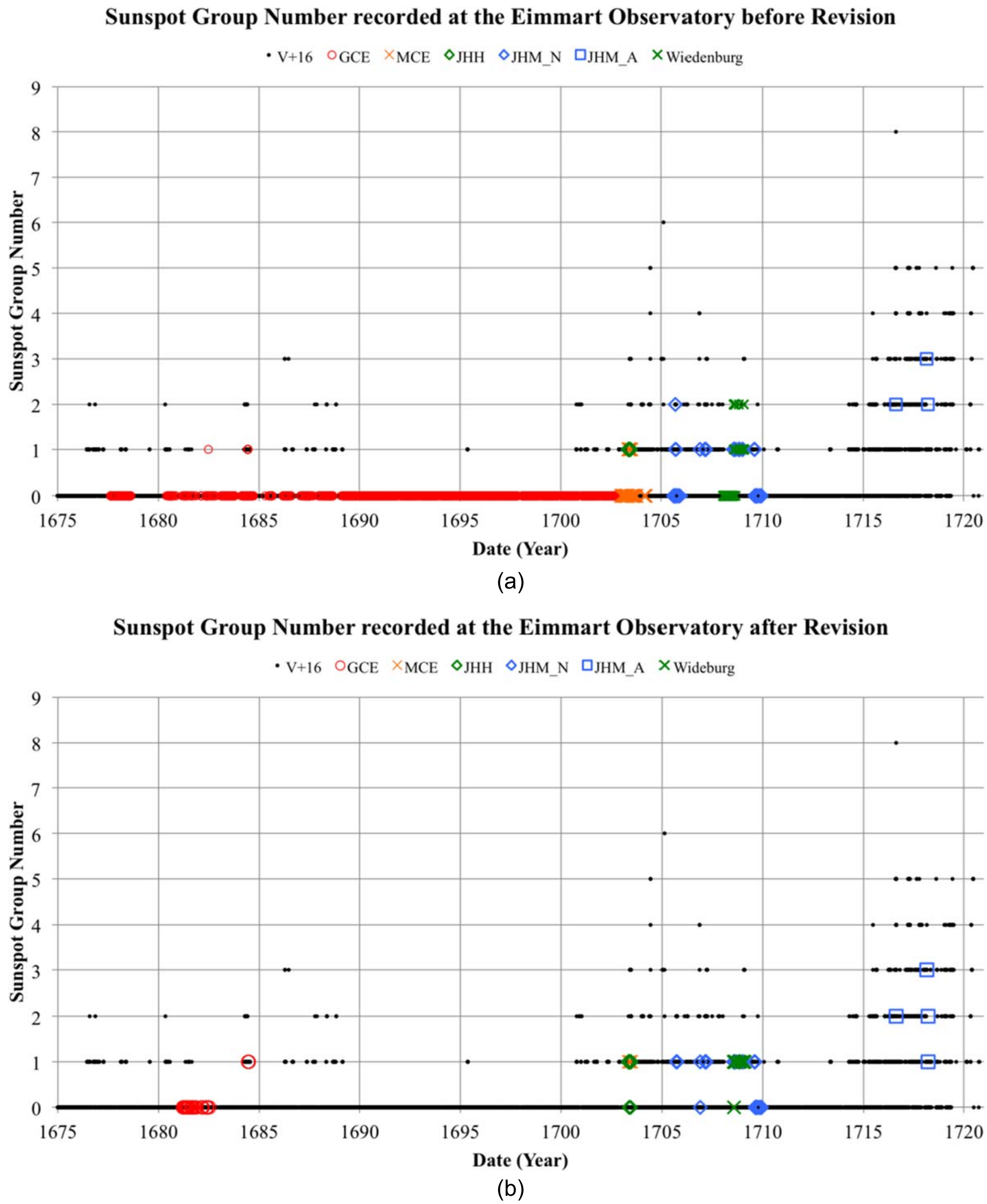

Figure 6. Sunspot group numbers recorded at the Eimmart Observatory and its neighborhood (a) before and (b) after our revision in comparison with the sunspot group numbers in the existing database (V+16), except for Rost. The data by GCE, MCE, JHH, JHM/N (JHM at Nürnberg), JHM/A (JHM at Altdorf), Wiedenburg/Wideburg, and V+16, except for Rost and Alischer, are shown using red circles, orange crosses, green diamonds, blue diamonds, blue squares, green crosses, and black dots, respectively. Note that "Wiedenburg" in V+16 should be corrected to "Wideburg."

axes. Therefore, we derived the east–west (E–W) orientations using the depicted motions of individual sunspots and north–south (N–S) orientations in comparison with other contemporary observations.

For example, JHM recorded two different drawings that included sunspot observations for the periods 1708 August 12–17 and September 4–5 (MS OR RNB, f. 998, t. 36, l. 136–137; Figures 3(b) and 7(a)). While the E–W annotations are correctly shown in Figure 3(b), the ones indicated in Figure 7(a) contradict the conventional sunspot motion. Likewise, the N–S orientations are different between the two drawings. Here we have followed the N–S orientation in Figure 3(b), which agrees with Wideburg's contemporary sunspot drawing (Figure 7(b); Wideburg 1709). Wideburg observed sunspots, depicted their motions in erect images (Figure 7(b)), and located these sunspots in the southern solar hemisphere, as also assumed by Spörer (1889). Likewise, Cassini reported sunspot positions between −6° and −7° for

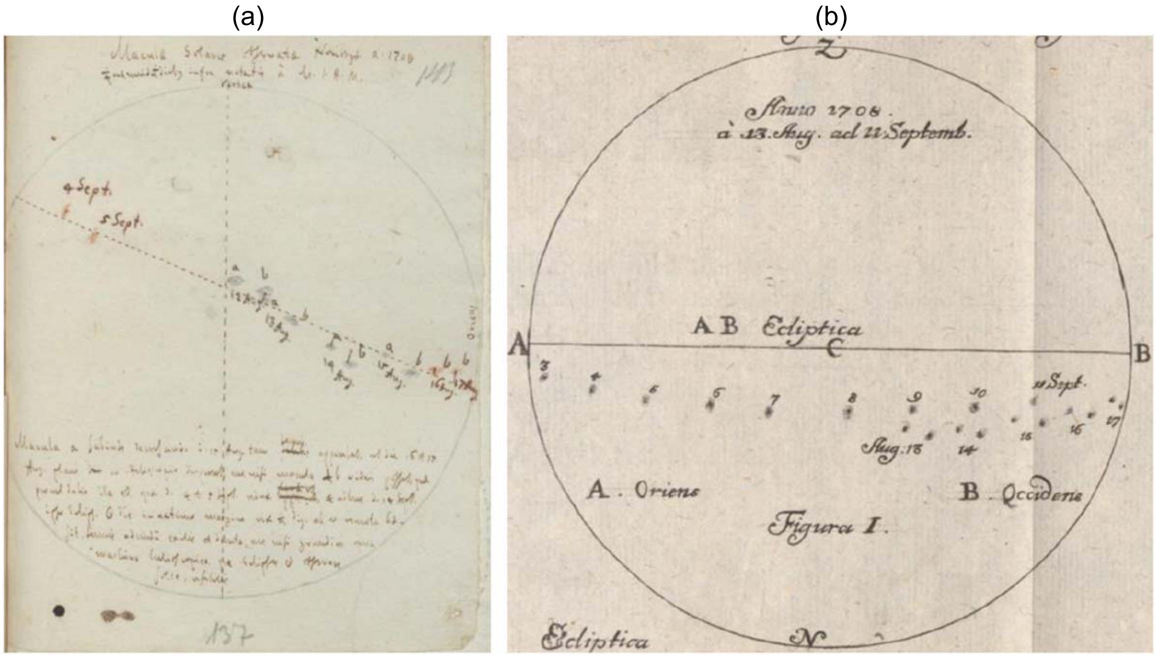

Figure 7. (a) JHM's sunspot drawing with incorrect E–W orientation on 1708 August 12–17 and that for 1798 September 4–5 in an upside-down configuration (MS OR RNB, f. 998, t. 36, l. 137). (b) Wideburg's sunspot drawing in an erect image for 1708 August 13–17 and September 3–11 (Wideburg 1709).

Table 1
Examples of the Extracted Data Set We Have Derived in This Manuscript Have Been Summarized in the Online Supplements (https://www.kwasan.kyoto-u.ac.jp/~hayakawa/data)

Year	Month	Date	*G*	Reference	Volume	Folio/Page	Observer
1681	3	21	0^{*}	MS OR RNB, f. 998	48	6	GCE
1684	7	2	1	MS OR RNB, f. 998	16	1b/71	GCE
1703	7	9	1	MS OR RNB, f. 998	35	24/40-40b	MCE
1703	5	26	1	MS OR RNB, f. 998	Mar-35	43/423	JHH
1705	10	9	1	MS OR RNB, f. 998	35	58	JHM
1708	8	13	1	Wideburg	1709	Fig I	Wideburg
1716	9	3	2	Müller	1723	Figure 3	JHM/A

Note. Here *G* is the sunspot group number, Reference indicates the source documents, Volume indicates the volume number or the publication year, Folio/Page is the folio/page number, and Observer is the observer's name. When the data entry is not filled, it shows the gap of observational data for the specified observational date. The data with asterisks should be treated with caveats.

1708 August 11–18 and the occurrence of another sunspot group for 1708 September 14–18 (HARS 1708, p. 107–108). Their chronological agreement implies that these sunspot groups are identical to one another. In this case, this sunspot group is located in the southern solar hemisphere and indicates the vertex description as the solar south. Similar conclusions are derived from comparisons of other sunspot drawings, for example, on 1709 January (MS OR RNB, f. 998, t. 36, l. 153 versus Wideburg 1709, Figures 3 and 4; see also Spörer 1889) and from GCE's drawing for 1684 July 2–8 (Figure 3(a)). The latter is compared with the sunspot observed in July in Paris, which was located in the southern hemisphere at $-10°$ (Spörer 1889) or between $-12.°4$ and $-10.°2$ (Ribes & Nesme-Ribes 1993; Vaquero et al. 2015b). This implies that the true solar north and south in GCE's drawing are located upward and downward, respectively, despite the downward annotation of the *Sep* (north).

For our position calculations, we used the software Soonspot, which allows one to calculate sunspot positions from the orientation of an image following the Earth or Sun axis (Galaviz et al. 2020). When sequential motions of the same sunspot groups are shown, we can calculate their latitudes, minimizing their daily latitudinal variations within the sequence. For observations made at noon, we can assume that the drawings are oriented according to the Earth's axes and can thus calculate sunspot positions. We have also chosen this orientation to calculate sunspot positions for some isolated drawings, such as one by JHM on 1709 January 6, where no information is available on its orientation. Thus, the measurement made in this case should be taken with caution because of this uncertainty. These analyses show the orientations of the sunspot drawings in the Eimmart Collection, probably as N–S inverted images by GCE in 1684 and JHM in 1705–1709 and erect images by JHH in 1703 and JHM in 1708 August–September.

On this basis, we computed the sunspot positions in the Eimmart Collection and compared them with the existing butterfly diagram for the MM (from Spörer 1889; Ribes & Nesme-Ribes 1993; see their digitizations in Vaquero et al. 2015b). As shown in Figure 8, the average of the single sunspot

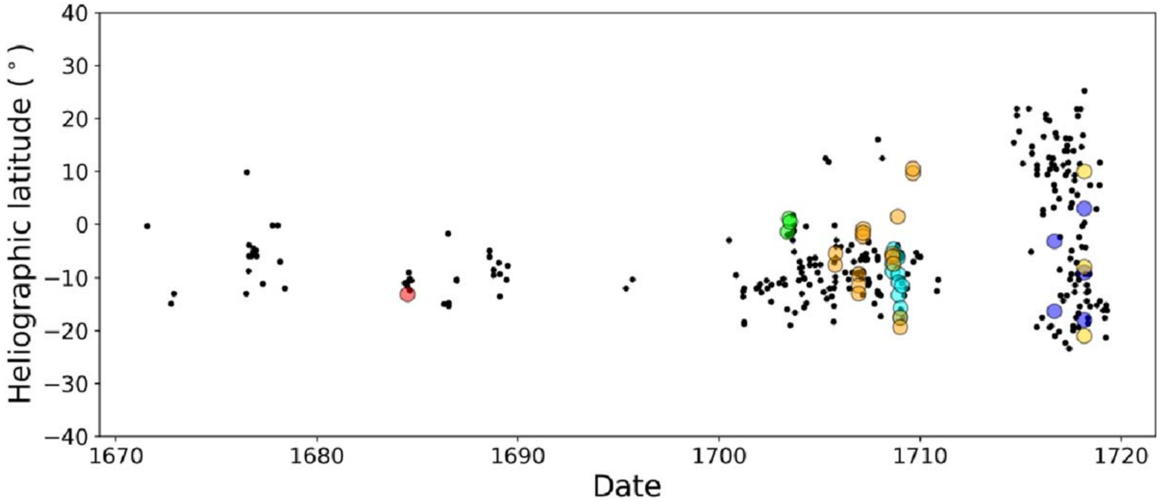

Figure 8. Sunspot latitudes calculated from sunspot observations recorded by the Eimmart Observatory and its neighborhood from 1684 to 1718: red for GCE, green for JHH, orange for JHM at Nürnberg, dark blue for JHM at Altdorf, light blue for Wideburg from 1708 August–1709 February, light yellow for Wagner (1718), and black for Spörer (1889) and Ribes & Nesme-Ribes (1993) digitized by Vaquero et al. (2015b).

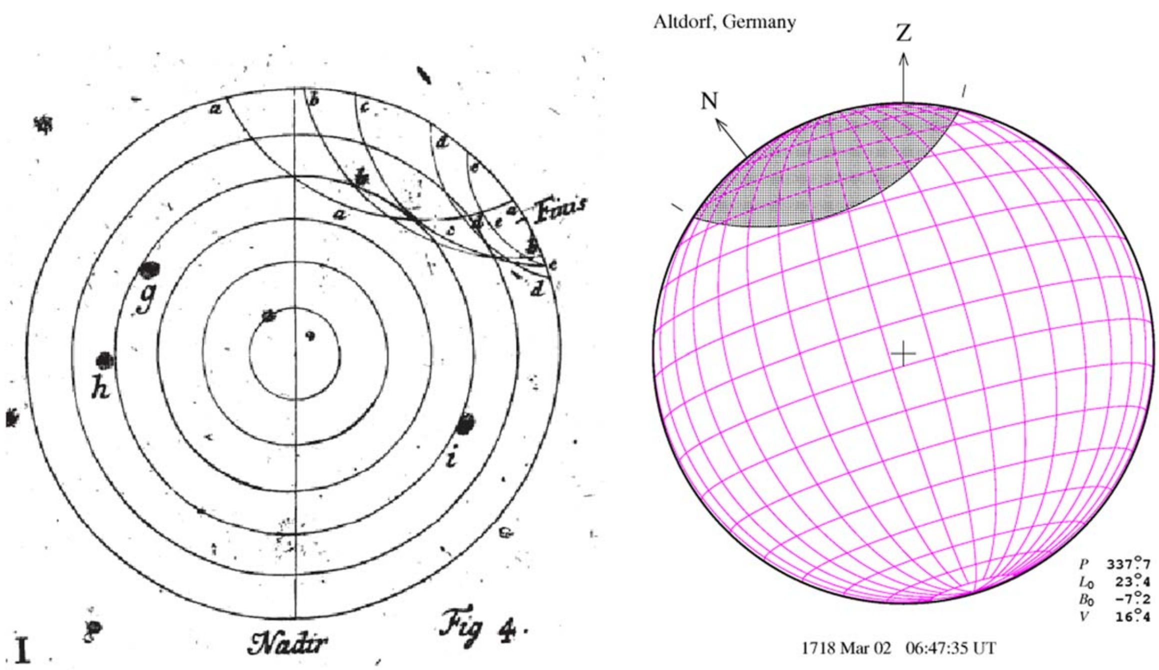

Figure 9. JHM's sunspot drawing on 1718 March 2 (Müller 1723) and our calculations for the solar disk orientation, heliographic coordinates, and position of the lunar shade as observed from Altdorf.

positions derived from the Eimmart Collection locates the sunspots mostly in the southern solar hemisphere or around the solar equator, except for groups in 1709 August. Among them, JHM's sunspot latitudes in 1708 November and 1709 August do not agree well with those of Wideburg (Figure 8). If we set the disk orientation from JHM's drawings differently (solar north at the top) against his other drawings, their heliographic latitudes are located around the solar equator. The latitudes obtained in this manner would also be different from those of Wideburg and Ribes & Nesme-Ribes (1993). This case presents a caveat regarding the uncertainty of their disk orientation. Notably, JHH's sunspot positions seem to indicate a possible recurrent active region near the solar equator from 1703 May 26 to July 16, as well as its intrinsically long lifespan of ⩾52 days. This is another example of the observed recurrent active region during the MM compared with the one occurring during 1671 August–September (Hayakawa et al. 2020c).

It is more challenging to derive sunspot positions from JHM's observations at Altdorf during 1716–1718 (Müller 1723), as they are chronologically isolated. In this interval, JHM recorded two drawings on 1716 September 3 and 1718 March 2. The latter is accompanied by JHM's observation of a partial solar eclipse, which allows us to determine its disk orientation more precisely and chronologically coincides with Wagner's sunspot drawing (Figure 2 of Wagner 1718). Here, as in Figure 9, we computed the orientations of the solar disk, their heliographic coordinates, and the relative position of the lunar shade, as observed from Altdorf (N48°33′, E12°06′; Müller 1723) and Berlin (N52°31′, E13°22′;

Figure 2 of Wagner 1718) using the ephemeris data of JPL DE430 (Folkner et al. 2014), the rotational elements in Archinal et al. (2011a, 2011b), and the variation of terrestrial and universal time (ΔT) in Stephenson et al. (2016), as previously performed in Hayakawa et al. (2019). On this basis, we have clarified them as E–W reversed images and calculated the sunspot positions accordingly. The results are moderately consistent with those calculated from Wagner's record. On the other hand, JHM's sunspot drawing on 1716 September 3 itself does not provide sufficient information to identify its exact orientation, except for its observational time at 10 LT. In comparison with Blanchini's report on the same date (Blanchini 1737), we assume the disk is oriented upside down according to the Earth's axis and have derived the sunspot positions accordingly; however, this lends little credit, and some caution should be exercised regarding the actual sunspot positions in 1716. Overall, the sunspot observations recorded at the Eimmart Observatory, by JHM at Altdorf, and by JHH and Wideburg indicate concentrations of the reported sunspots in the southern solar hemisphere and a return of sunspots to the northern solar hemisphere after 1716. These results generally confirm the existing scenarios derived from contemporary sunspot observations at Paris Observatory (Ribes & Nesme-Ribes 1993).

6. Conclusion

In this study, we analyzed the sunspot observations recorded at the Eimmart Observatory and in its neighborhood during the MM. We have identified the observers as GCE, MCE, and JHM and examined their manuscript records pertaining to the Eimmart Collection available from the Manuscript Department of the National Library of Russia (MS OR RNB, f. 998). These three observers conducted early sunspot observations from the Eimmart Observatory at Nürnberg from its onset (1677–1709), which were accompanied by JHM's observational summary made at the university observatory at Altdorf (Müller 1723). Their collections provide direct sunspot observations and those from the surrounding neighborhood, including observations made by JHH.

However, it is not precisely clear which instruments were used for each observation. Observatory assistants' contemporary records indicate the use of a small helioscope and dark chambers when conducting sunspot observations to reduce natural light and project images onto a screen, at least from 1691 to 1751 (e.g., Glaser 1691; Rost 1718). This indicates that the observers at the Eimmart Observatory had the capacity to project solar images when conducting their observations.

We identified datable sunspot observations for 7 days and solar observations with general descriptions indicating a spotless Sun for 33 days in GCE's logbooks, 5 days in MCE's logbook, 66 days in JHM's logbooks, 4 days in JHM's observational summary at Altdorf, 22 days in JHH's pamphlets, and 25 days in Wideburg (1709) to derive their sunspot group numbers according to the Waldmeier classification. Through our investigations, we have identified and removed considerable contamination introduced by other types of observations, such as those for solar altitude and diameter. This has dramatically reduced the number of datable observations in the Eimmart Collection. We have also identified the plausible spotless days from 1681 to 1682 based on a combination of general statements and periods of solar observations. We have also identified the list of the robust spotless days in JHM's summary notes in 1709. In addition, we have modified the existing data for JHH at Berlin, JHM at Altdorf, and Wideburg at Helmstadt using their original source documents.

These efforts have, on the one hand, dramatically removed a considerable amount of apparently spotless days from existing databases and challenged the underestimation of the sunspot group numbers during the MM. On the other hand, the derived sunspot group numbers remain as $\leqslant 1$ before 1715 but exhibit higher values after 1715. This result supports the existing paradigm of considering the MM as a grand minimum (Usoskin et al. 2015; Vaquero et al. 2015a), rather than as relatively higher solar cycles derived from several reconstructions (Zolotova & Ponyavin 2015; Svalgaard & Schatten 2016). Our revision has updated the temporal coverage of 73.4% in the existing sunspot observations during 1677–1709 (V+16) to 66.9%. This decrease is more significant during 1685–1702, where such temporal coverage has been reduced from 71.4% to 61.5%.

Because of insufficient recorded details, the orientations of the sunspot drawings made at the Eimmart Observatory have been determined based on a comparison with contemporary sunspot observations. On this basis, sunspot positions were mostly concentrated in the southern solar hemisphere and solar equator. The sunspot occurrences in both hemispheres significantly support the current paradigm with respect to the end of the MM in 1715, in terms of sunspot distributions (Ribes & Nesme-Ribes 1993; Arlt & Vaquero 2020) and solar coronal structures (Riley et al. 2015; Hayakawa et al. 2020b). These confirmed hemispheric asymmetry and sunspot concentrations in the low latitudes in the southern hemisphere benefit further theoretical discussions of the dynamo theory (e.g., Sokoloff & Nesme-Ribes 1994; Sokoloff 2004; Nagovitsyn 2008; Karak 2010; Nagovitsynet al. 2010; Cameron et al. 2017; Charbonneau 2020).

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Data Availability

The original source manuscripts studied in this article are available in the Eimmart Collection at the Manuscript Department of the National Library of Russia (MS OR RNB, fond 998).

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