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Sunspot Observations at the Eimmart Observatory: Revision and Supplement

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Abstract
Digital images of sunspot drawings of the archives of Georg Christoph Eimmart stored at the National Library of Russia, St. Petersburg, are analyzed to obtain sunspot-group numbers and sunspot areas as well as heliographic positions. Overall, more than a hundred drawings were processed. The impact of drawing and reproduction uncertainties and the aims of historical observations are considered. The sunspot positions are compared to those reported by contemporary observers of the Maunder minimum. The restored sunspot-group numbers and latitudes are compared to those extracted by Hoyt and Schatten (*Solar Phys.* **179**, 189, 1998) as well as Hayakawa et al. (*Solar Phys.* **296**, 154, 2021b) and Hayakawa et al. (*Astrophys. J.* **909**, 166, 2021d). The persistence of long-lived sunspots over several solar rotations is discussed.

Keywords Sunspots · Solar cycle · Observations

1. Introduction

In recent years, significant efforts have been made to extend the knowledge of long-term solar activity (Arlt and Vaquero, 2020). The sunspot numbers developed by Wolf (1851) and the group numbers by Hoyt and Schatten (1998) have been revised (e.g. Clette et al., 2014; Svalgaard and Schatten, 2016; Vaquero et al., 2016; Wang and Li, 2021; Tlatova et al., 2022; Herrera et al., 2022). Historical archives of sunspot observations (link.springer.com/collections/fgbiffeejd) are actively studied (e.g. Arlt, 2018; Fujiyama et al., 2019; Karoff et al., 2019; Friedli, 2020; Nogales et al., 2020; Bhattacharya et al., 2021; Carrasco et al., 2021; Hayakawa et al., 2021a,c; Aparicio et al., 2022; Carrasco et al., 2022; Illarionov and Arlt, 2022, 2023). Moreover, phenomena related to solar activity have been scrutinized such as space weather (Hayakawa et al., 2020; Silverman and Hayakawa, 2021; Hayakawa et al.,

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2022) and auroral reports (Bekli and Chadou, 2019; Bhaskar et al., 2020; Cliver et al., 2020) naturally related to solar activity. Processing methods for this kind of data are also multiplying (Vokhmyanin and Zolotova, 2018; Galaviz et al., 2020; Illarionov and Tlatov, 2022; Wagner, Neuhäuser, and Arlt, 2022).

Recently, Hayakawa et al. (2021b,d) evaluated sunspot-group numbers and sunspot-group positions from the archives of Georg Christoph Eimmart (1638–1705), a German astronomer, mathematician, painter, and engraver from Nürnberg. The archives were gathered from the Collection 998 of the Manuscript Department of the National Library of Russia, St. Petersburg (MD NLR, 1958), which stores 59 volumes containing documents left by the Eimmart family and their assistants as well as correspondence with representatives of science, culture, art, and politics from a number of European countries during the period 1583–1723.

Since the uncertainties in historical data can be significant (Ogurtsov, 2013), the reconstructed sunspot parameters obtained by various researchers may differ (Sakurai, 1980). In this article, we take an independent look at the observations of the Eimmart archive and compare our results with those by Hayakawa et al. (2021b,d). Moreover, we add observations by Saxonius, Wurzelbau, Manfredi, and Maria Eimmart, also belonging to this archive. In all drawings, we derived the position and area of each sunspot. If the umbra and penumbra were captured by the observer, we evaluated their areas separately. The resulting coordinates of sunspot groups were compared with those provided by contemporary observers of the Maunder minimum. Note that some historical researchers gave sunspot positions in "digiti", "inches", or "Zoll", all denoting the same way of dividing the solar disk into six concentric circles, where the largest circle is identical to the solar limb. The solar diameter, therefore, becomes divided into 12 parts. In some figures below, we reproduce this measurement system.

When analyzing historical sunspot drawings, a major goal is to define the actual orientation of the heliographic grid in each individual observation. Similarly to Vokhmyanin, Arlt, and Zolotova (2021), we define sunspot positions in two ways. Both methods aim to find the optimal rotation of the heliographic grid with the lowest day-to-day variability of sunspot latitudes. In Method I, the range of possible orientations is limited by the ±30-minute interval centered around the noted time of the observation. In Method II, however, we leave out temporal restrictions and consider the whole range of rotation angles. This approach is justified by our ignorance of how the paper was placed behind the telescope (in the case of projecting the image), how the telescope itself rotates the image, and how the drawings were copied into a logbook or into a letter to another observer. Although both methods adjust the orientation of the heliographic grid, omitting the longitudinal displacement of sunspots, we recommend relying on longitudes provided by Method I. Longitudes are measured from the zero meridian of the heliographic longitudes at Greenwich Noon on 1 January 1854 and rotating with a sidereal period of 25.38 days as conventionally fixed by Carrington (Meeus, 1991). The mathematical procedure is described in detail by Vokhmyanin and Zolotova (2018) and Vokhmyanin, Arlt, and Zolotova (2020), where we also describe approaches to clustering sunspots into groups based on the classification by McIntosh (1990) and to measure sunspot areas in millionths of a solar hemisphere (microhemispheres, msh).

In the sections below, we analyze drawings made by observers from the Eimmart archive collection 998 (MD NLR, 1958). For each observer, the volumes (v.) and folios (f.) on which the corresponding drawings are located are indicated. The calendar dates refer to the Gregorian calendar. Sunspot data are provided in the Electronic Supplementary Materials.
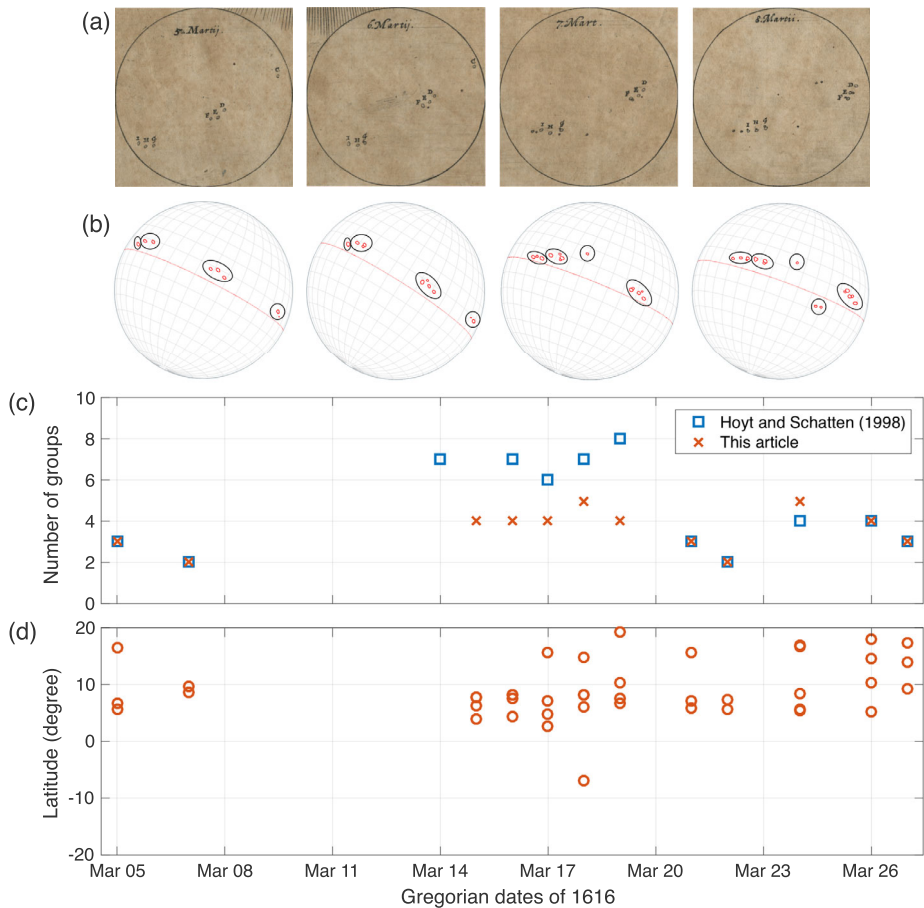
Figure 1 (**a**) Original drawings by Saxonius (Eimmart Archive Coll. 998, v. 11, f. 99; here and below courtesy of MD NLR); (**b**) clustering of sunspots into groups and reconstructed heliographic grid assuming projection behind a Galilean telescope; (**c**) the number of groups defined by Hoyt and Schatten (1998), for which we shifted dates to the Gregorian calendar, and in this work; (**d**) spatio-temporal distribution of sunspot groups.

2. Petrus Saxonius, 5 – 27 March 1616

A reproduction of twelve sunspot drawings by Petrus Saxonius (German version: Peter Sachse) is stored in v. 11, f. 99. The diameter of the solar disks is about 5 cm. The original dates refer to the Julian calendar. As can be seen from the examples of drawings, sunspots are marked with letters (Figure 1a).

Neuhäuser and Neuhäuser (2016, Figure 7 therein) analyzed the full copy of this reproduction available in the German National Museum in Nürnberg. They concluded that the drawings by Saxonius are oriented upside down after comparing them with the observations by Tarde (1620). After an appropriate rotation, the spots move from the left to the right. This may imply that Saxonius exploited a projection apparatus behind a Galilean telescope.

Figure 1b shows sunspot groups assigned by us. In complex activity nests (Castenmiller, Zwaan, and van der Zalm, 1986), however, various researchers may assign different numbers of groups. Figure 1c compares the groups defined by Hoyt and Schatten (1998) and
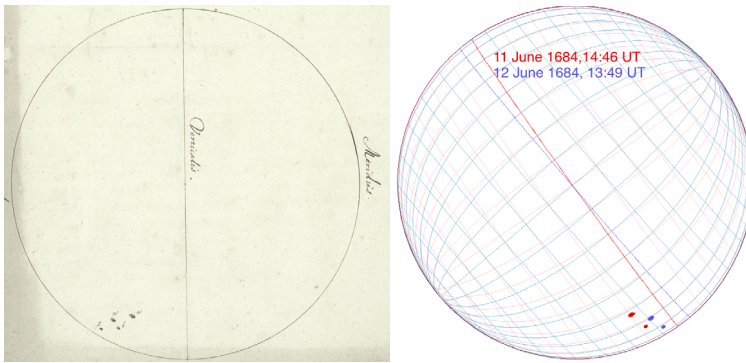
Figure 2 (*Left*) Original drawing by Wurzelbau (Eimmart Archive Coll. 998, v. 5, f. 47); (*Right*) reproduction of a horizontally mirrored image with imposed heliographic grids.

by us. The former used the original dates, but we shifted them to the Gregorian calendar since Nürnberg and Altdorf were protestant at the time. The blue square of 14 March 1616 (Gregorian) is apparently a misprint in Hoyt and Schatten (1998); it should be the next day. Significant discrepancies occur on 15 – 19 March 1616. We suppose that Hoyt and Schatten assigned groups in accordance with Saxonius's lettering while we clustered several spots into probable groups. The historical archive of sunspot observations (HASO) of Vaquero et al. (2016) provides the same group numbers (version 1.21) as Hoyt and Schatten, but corrected the dates to the Gregorian calendar, as we also did.

Saxonius observed at the University of Altdorf near Nürnberg and did not provide any notes on the time of drawings, except on the first one on 5 March (see below). Thus, we can only suppose that the images are oriented as they were seen on the projection screen. Applying Method II, we reconstruct the orientation of the solar axis, which provides us with the time of observation and the sunspot positions. We obtained the transit of 12 sunspot groups, of which only one was located in the southern hemisphere (Figure 1d).

In the drawing of 5 March (Gregorian), Saxonius wrote "24 Februar. in. m.", which could mean the drawings are made in the morning "in mane" or at Noon "in meridie". The time calculated by Method II is about 11:00 UT, i.e. around local Noon. The figurative Sun in the middle of the reproduction repeats the drawing of 5 March. The sunspot positions therein deviate by a maximum of 3°, while sunspot areas on the figurative Sun are increased by a factor of two to three, giving us an idea of the accuracy of the drawings.

3. Johann Wurzelbau, 11 – 12 June 1684

One drawing by Johann Philipp von Wurzelbau is stored in v. 5, f. 47. The description says: "Schema Macularum in Sole visarum ope telescopii sinistra dextris permutantis", i.e. a figure of the sunspots viewed by means of a telescope swapping left and right. This suggests that projection was used; therefore, on the horizontally mirrored image, Meridies (the Noon direction) is located on the eastern limb, as expected for an afternoon observation (left panel of Figure 2). Further, the description says that sunspots *a* and *b* were observed at 4 p.m. of 1 June, while *α* and *β* were observed at 2 1/2 p.m. on 2 June 1684 according to the Julian calendar. These dates are 11 and 12 June of the Gregorian calendar. In order to reconstruct the heliographic grid, we assume that Wurzelbau observed in Nürnberg in his house
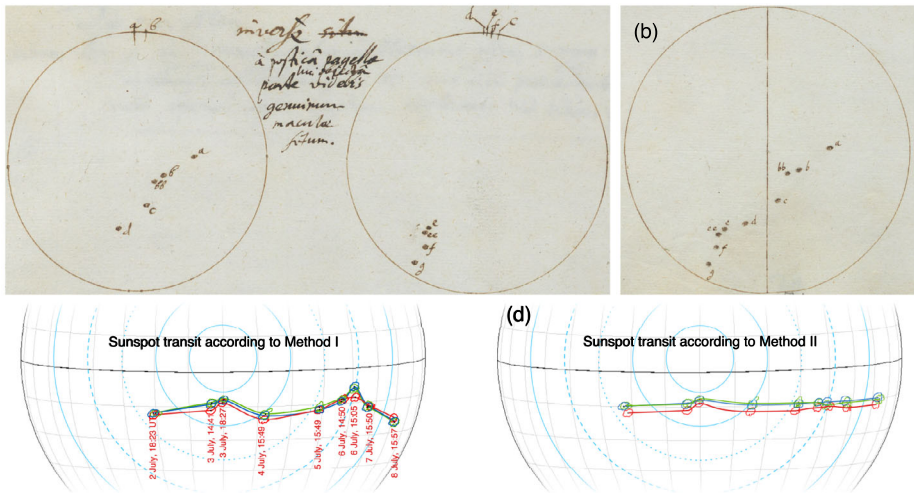
Figure 3 (**a**) and (**b**) Reproduction of three original drawings by Georg Christoph Eimmart (Eimmart Archive Coll. 998, v. 16, f. 71); (**c**) sunspot positions and the time of observation defined by Method I in UT. *Colors denote the reconstructed sunspot trajectories* for three combinations of the original drawings. The heliographic grid corresponds to 5 July 1684; the solar axis is set vertically, i.e. excluding diurnal rotation. *Blue thin circles* mark inches. (**d**) Reconstruction of the sunspot transit by Method II.

at Spitzenberg 4 (Gaab, 2002). Since just two observing days are available, we use only Method I, yielding the time of observation in UT format. The only image orientation giving an acceptable motion of the sunspots on nearly constant latitudes is shown in Figure 2. The average latitude of the sunspot group is $-9°$, and the longitudes of the two sunspots vary from 260° to 280°.

4. Georg Eimmart, 2 – 8 July 1684

A single sunspot transit was reported by Georg Christoph Eimmart at his observatory in Nürnberg. For information about the observational equipment, see Hayakawa et al. (2021d). Five drawings are stored in v. 16, f. 1 (two drawings) and f. 71 (three drawings). The illustrations are accompanied by a date and a time; sunspots *a* and *bb* are also reported to have been observed when the altitude of the Sun was 12° and 11°, respectively. Figures 3a and b show original drawings from folio 71. In Figure 3a, each sunspot is placed on the disk according its own vertical ("ejus verticalis") marked on the top of the limb with letters. A short note says that there is a full copy of these two drawings (folio 1). In Figure 3b, sunspot positions were corrected so that all verticals coincide.

As already noted by Hayakawa et al. (2021d), the annotations of compass directions in folio 1 (indicating a rotation by 180°) lead to positions incompatible with other observers at the time. We, therefore, reflected the images from right to left and considered three combinations of drawings: i) the two images from folio 1; ii) the two first images from folio 71 (Figure 3a); iii) the third image from folio 71 (Figure 3b). In the first two cases, we pre-aligned the verticals. Intercomparison of these three versions aims at assessing the uncertainties related to redrawing.

Figure 3c shows sunspot trajectories and observing time (UT) reconstructed by Method I. Note that for 8 July we assume that the observation was done at 16:00 local time in accordance with the description, "hor. qs. ante ⊙ occ.", which most likely means "hora qui supra", i.e. the hour as before. Much later times would place the sunspot even below −20° and can be discarded. The largest discrepancy between the reconstructions is slightly above 3° in latitude and reaches 1.5° in longitude.

The first and the third observations are reported to belong to the evening of two successive days. According to the synodic rotation, the sunspot should have moved about ≈ 13°, but the reconstruction yields a shift in longitude slightly over 20° (Figures 3c). Such a discrepancy may be caused by either the inaccuracy of the drawing or by an incorrect note on the time of observation. A substantial shift of 17° in the central meridian distance (CMD) is also found between the sunspots on two successive days: 4 and 5 July. According to the description, two observations on 6 July are separated by only 15 minutes, while the sunspot displacement in CMD exceeds 4°. These inconsistencies cast doubt on either the accuracy of the timing or the accuracy of the drawing.

Figure 3d shows the sunspot transit reconstructed by Method II. Recall that this approach minimizes cumulative discrepancy of sunspot latitudes and is not tied to the times of observation. The third sunspot location (evening of 3 July) deviates from the most relevant track. This sunspot is located close to the disk center, and no image rotation can compensate for the displacement. If we force the method to ignore this sunspot, the average latitude of all spots will be between −11 and −12° for all three combinations of drawings.

Neuhäuser, Arlt, and Richter (2018) analyzed reports by Kirch and Schultz that describe that on 5 July (time is unknown, presumably local Noon) the sunspot was three inches from the disk center (thin blue dotted circle in Figure 3c), and that on 6 July at 6 p.m. local time (around 17:20 UT), the sunspot was four inches from the disk center (thin blue dashed circle). This description closely matches Eimmart's drawings.

Combining the mentioned discrepancies, we assume the uncertainty of sunspot observation by Eimmart is, on average, 3−4° in both latitude and longitude. For the drawing from Figure 3b, the average latitude provided by Method I is −11.2 ± 2.4° (red curve in Figure 3c). Hayakawa et al. (2021d) inferred that this spot emerged around −13° in latitude. The average longitude, as given by Method I, is about 280 ± 3.5°. This yields about 14.46° d^{-1} solar differential rotation at 10° absolute latitude following the estimation by Balthasar, Vazquez, and Wöhl (1986). We find that using the Carrington angular velocity of 14.1844° d^{-1} the spot must have been at a 7° lower longitude on 12 June (Section 3), i.e. at 272−274°, which is within the range of 260−280° as derived from the Wurzelbau report.

Spoerer (1889) wrote that Kirch observed this sunspot from 6 May to 27 July 1684 during four rotations. On the second rotation, a spot appeared on 11−13 June 1684. With reference to Cassini, Spoerer provided a latitude of −11° on 5−17 May, −10.8° from 28 June to 9 July, and −9° on 26−28 July 1684. Analyzing drawings by Kirch and Ihle, Neuhäuser, Arlt, and Richter (2018) provided the latitudes −21.9° (Ihle) and −19.2° (Kirch) on 6 May 1684. They argued that the sunspot of 5 and 6 July may not have been the same as that on 6 May, since these spots do not match in longitude. Our rough estimation of these reports gives a sunspot Carrington longitude of 260−290° on 5−6 July (Kirch and Schultz) and ≈ 40° on 6 May 1684 (Kirch and Ihle).

Therefore, we suggest that the observers reported on more than one sunspot group at latitudes of about −10° and −20°. An object living for four rotations may be rather an active longitude. Otherwise, it should have been a large complex of activity showing some sort of evolution. Note, however, that the observers did not always draw the real sizes of sunspot groups.

5. Johann Hoffmann, 26 May – 16 July 1703

The first portion of the observations by Johann Heinrich Hoffmann was made in Berlin, where he rented a flat from Kirch (Dick, 2000), and they are stored in v. 3, f. 422 – 424. Three drawings of one sunspot transit are made with black ink. The first two drawings are accompanied by tables that provide the day, time of observation, and three columns with sunspot positions measuring the linear distance from the eastern limb. The first column contains raw values in micrometer turnovers scaled to 77, the second arcminutes and arcseconds scaled to the solar diameter of 31′42″, and the third in digiti scaled to 12 (see Section 1). Figures 4a and b evaluate the reliability of Hoffmann's tabular computations. Apart from very few discrepancies, the sunspot positions are the same as the ones from the drawings.

This scientific report has been attached to a letter to Georg Eimmart. On folio 425, Hoffmann wrote: "Sonder Zweifel wird mein Patron die wenigen Zeilen, durch Einschluß des Hn Deckers, von den 10 Julij, erhalten haben; darin ich etwas von der Observatione Macularum in Sole gedacht, und zugleich einen Abriß oder Schema wo die Maculae täglich gestanden übersendet, in welchen Schemate der H Decker sich selbst erboten, die Maculas auf die annotirte loca genau zu verzeichnen, weil ich ihm öfters zu der Observation rufen, und zu sehen laßen, aber er hat weder die formam noch den situm recht in acht genommen; denn die große Macula war in dem medio ☉ meist rund, und prope margines oval, auch sind ihr die kleinen alle Zeit von hinten gefolget. Dahero ich wieder das damahls übersendete Schema hirmit protestire, und werde meinen Patrono bey übersendung der Ephemeridum ad annum 1704 die Observationes von diesen Maculis (davon die große Macula auch das dritte mal in ☉ erschienen) wie auch von der Eclipsi ☽ des 29 Junij mit bey legen."

We translate as follows: "Without doubt, my patron will have received the few lines of 10th July through the action of Mr Decker, in which I commemorated some observations of spots in the Sun, and as well sent a sketch or scheme with the daily locations of the spots, in which Mr Decker offered to plot the positions precisely. I had often called him to see the observation, but he neither scrutinized the shapes nor the locations; since the large spot was in the middle of the Sun mostly round, and oval near the limb. Also, the small ones always followed it behind. Therefore, I herewith again present the transmitted sketch and will, upon receiving the annual ephemeris of 1704, attach the observations of these spots (of which the large one appeared for the third time on the Sun) as well as of the lunar eclipse of 29th June for my patron."

Indeed, a copy of the table appears in v. 35, f. 42 – 43, and the next folio titled "Observationes Coelestes Anni 1704" is blank. The only difference is that in the first table for 25 June 1703, the local time of observation is 7:10 p.m., while it is 7:0 p.m. in the second table.

The "transmitted sketch" made with a pencil was placed in v. 37, f. 73 – 74. An enlarged piece is shown in Figure 4c. The sunspot group of 27 May 1703 accurately reproduces the drawing Hoffmann sent to Kirch (Neuhäuser, Arlt, and Richter, 2018, Figure 15 therein). Recall that Hoffmann wrote that the small sunspots always followed behind the large spot, while the ink drawing shows the transit of only the largest sunspot.

Figures 4d – f compare the series of drawings drawn in black with the drawings with a gray pencil and the largest sunspot positions according to the digiti units from the tables (red dashes). Tabular and drawn sunspot positions match adequately except on 28 June 1703. The tabular data mention that the sunspot was observed at 19:00 and located at 10 44′ digiti. However, in the drawing and according to the micrometer measurements, the sunspot was located closer to the western limb. Since the micrometer measurements and the conversions to arcminutes and arcseconds are consistent with each other and the drawing, we suppose there is an error in the digiti column. In the Electronic Supplementary Materials, we provide
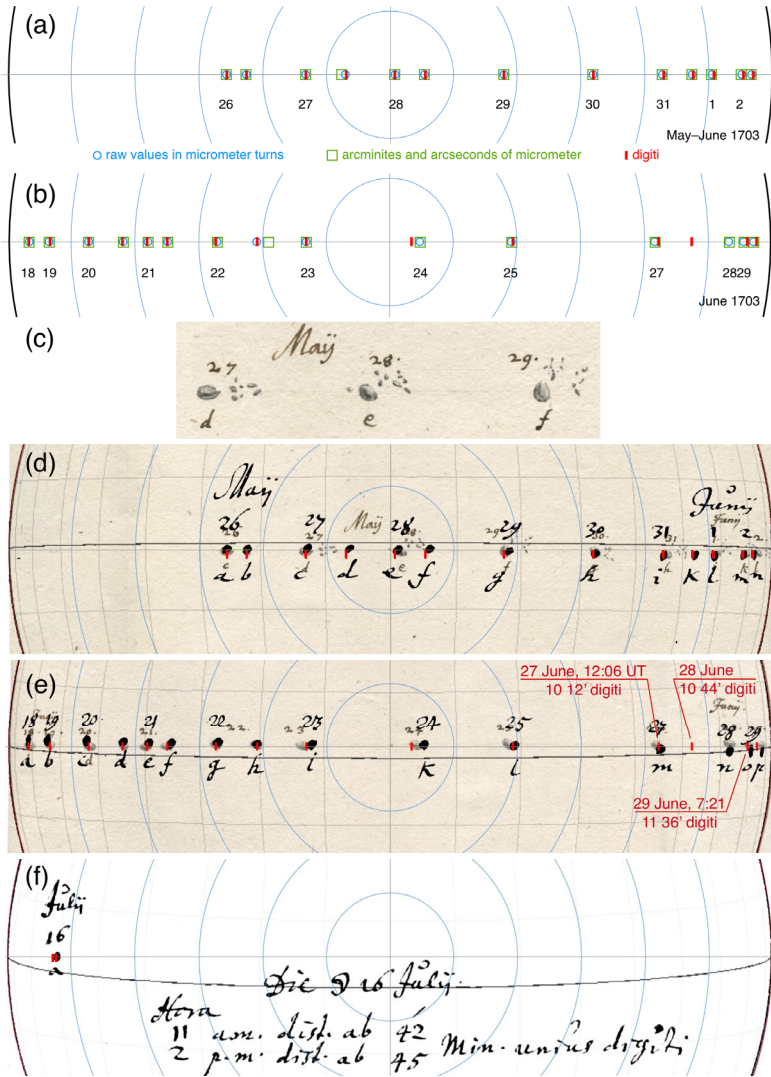
Figure 4 Hoffmann's tabular computations of the positions of the largest sunspot in micrometer turns (*blue circles*), in arcminutes and arcseconds (*green squares*), and in digiti (*red dashes*) from 26 May to 2 June 1703 (**a**) and from 18 to 29 June 1703 (**b**). Panel **c**: an enlarged pencil drawing of the sunspot group of 27 – 29 May 1703. Panels **d – f**: superimposed ink and pencil drawings of the sunspot transit from 26 May to 2 June 1703, from 18 to 29 June 1703, and the sunspot of 16 July 1703, respectively. The images are reproduced from the Eimmart Archive Coll. 998, v. 3, f. 422 – 424, and v. 37, f. 73 – 74. *Red dashes* indicate the tabular positions of the largest sunspot in digiti. The three heliographic grids correspond to 26 May, 18 June, and 16 July 1703. The grid intervals are $10°$. The solar Equator is shown as a *horizontal line*, *blue circles* mark digiti, and times reported by Hoffmann are converted to UT.

three sets of sunspot parameters reconstructed from the drawings in ink, pencil, and from the tabular data in digiti.

Note that Hoffmann located the sunspots on the horizontal line passing through the center of the disc. The largest sunspot turns out to be either slightly in the northern or slightly

in the southern hemisphere since the solar Equator crossed the disk center on 3 June 1703. Hayakawa et al. (2021d, Figure 8 therein) defined that the sunspot group observed from 26 May to 2 June 1703 was in the southern hemisphere, but the two others of $18-29$ June and 16 July 1703 were in the northern hemisphere, assuming the vertical points to the celestial pole. Based on the letters by Hoffmann and Kirch, Neuhäuser, Arlt, and Richter (2018) inferred that the sunspot group from 24 May to 2 June 1703 was located on average at $-0.7 \pm 3.5°$. In addition, they noted that Kirch had speculated that the sunspot that appeared between 18 and 29 June 1703 was the same one. Spoerer (1889) listed both sunspots from 24 May to 3 June and from 18 to 30 June 1703 with $-2°$ latitude referring to the reports by la Hire and Cassini.

The largest sunspot of the group visible from 26 May to 3 June 1703 was also drawn by Stannyan and Hodgson (1704). We estimated its latitude to be about $-2°$. On $24-30$ June 1703, the sunspot was reported by Derham (1703), who described it as "round and strong, afterwards long, and with a Nucleus. The very same Spot (I doubt not) I saw again on the Suns Eastern side on July 5 [16 July 1703 Gregorian]. . ." We determined the sunspot latitude from his drawing of $24-30$ June 1703 to be a couple of degrees in the southern hemisphere.

We also reconstructed the sunspot positions from Hoffmann's drawings. Only Method II can be exploited, as the orientation of the solar disk depicted does not match its actual appearance in the telescope. Using the drawings and the tabular data, we follow the hypothesis of a long-lived sunspot group and obtain an average latitude of the largest sunspot of $-0.85 \pm 0.2°$ for the period from 26 May to 16 July 1703.

We show below that this sunspot group was also observed by Maria Eimmart and Eustachio Manfredi (Eimmart Archive Coll. 998, v. 35 and v. 4, respectively). In Section 7, we compare their drawings and find that the times of observation noted by Hoffmann were probably misspelled (morning and evening were mixed up) in several cases. Here and in the Electronic Supplementary Materials for Hoffmann's observations, longitudes are indicated for the corrected times of observation. The average longitude of the largest sunspot from 26 May to 2 June is 270.5°, 274° for $18-29$ June, and 278° on 16 July 1703. Hence, Hoffmann, Kirch, and Derham could have reported on a complex activity nest (Castenmiller, Zwaan, and van der Zalm, 1986) or magnetic-activity complex (Bumba and Howard, 1969), where new magnetic flux emerges near a pre-existing active region (Muhamad et al., 2021). This may also be related to the phenomenon of active longitudes well seen in the period of overlap of 11-year cycles (Benevolenskaya et al., 1999; Kostuchenko and Benevolenskaya, 2014; Kramynin and Mikhalina, 2016). The year 1703 belongs to the ascending phase of Cycle -4. However, the near-Equator location of the sunspot group suggests that it might belong to the previous cycle overlapping with Cycle -4.

6. Maria Eimmart, 30 – 31 May and 9 July 1703

Three drawings by Maria Clara Eimmart, the daughter of Georg Christoph Eimmart and wife of Johann Heinrich Müller, a professor of astronomy at Altdorf (Bernardi, 2016), are stored in v. 35, f. $37-40$. The catalog record for these folios contains a question mark after her name. A comparison of the handwriting with letters by Maria Clara to Johann Jacob Scheuchzer in Zurich written in $1695-1697$ (Eimmart, 1695) shows little similarity with the observing folios considered here. There may be three reasons for the differences: i) the letters are written in German, whence using the Kurrent writing in contrast to the Latin observing notes, ii) the letters were more carefully written than the observing notes, and iii) the observations were made $6-8$ years after the letters had been written.

Figure 5 Short note and mirrored reproduction of the sunspot drawing with gray and red pencils of 9 July 1703 by Maria Eimmart (Eimmart Archive Coll. 998, v. 35, f. 40). The heliographic grid corresponds to 8:41 UT. *Blue thin circles* mark digiti. The bipolar sunspot group is indicated by the *red arrow*.
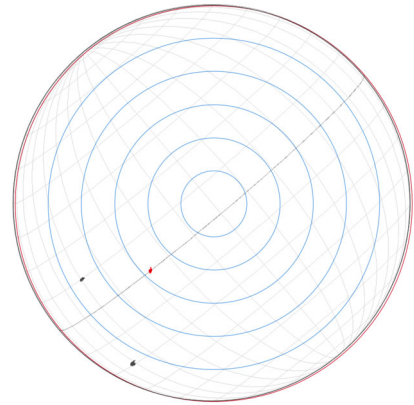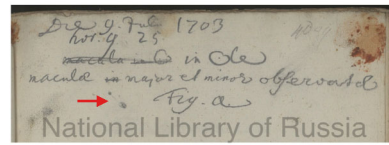
We can also use the observed culminations of astronomical objects to determine the geographical latitude of the observer. The solar altitudes checked appear to favor a location 3 arcmin south of the Eimmart observatory. The nearby observatory at Altdorf (operated by Johann Christoph Sturm until 1703) is 4.3 arcmin south of the Eimmart observatory. However, since J.C. Sturm died in 1703, the observations cannot be by him, as they cover the period of February 1703 to April 1704.

The measurement errors at Eimmart's observatory were determined to be up to 4 arcmin, with an average of 1.66 arcmin (Gaab, 2005). Their own latitude estimate of 49°27′20″ (von Murr, 1784) is very close to the modern value of 49°27′30″ though, but individual measurements may, of course, be of lesser quality. Therefore, the daily altitude measurements of objects may have also been made at Nürnberg. There is also the fact that G.C. Eimmart fell ill in 1703 before he died on 5 January 1704. This is confirmed by a letter to Flamsteed in October 1703, in which Eimmart apologizes for not sending observations because of illness, as well as a biography source saying that he had been ill for two years before he died (Gaab, 2005). Therefore, it is well possible that his daughter took over the daily measurements of culmination altitudes. Finally, there are, in fact, notes (Scheuchzer, 1691) with Latin block letters among the observations that resemble the Latin block letters on Maria's (upside-down) drawing of the first-quarter Moon in a friendship book of Johann Jacob Scheuchzer sufficiently well that we conclude the observations in v. 35, f. 7 – 35, 37 – 40, and 45 – 51 were made by Maria Clara Eimmart.

The sunspot drawings are schematic, made with pencil. Short accompanying notes provide a date, an observing time, and a sketch of sunspots. Throughout the folios, there are a lot of defects of gray and various blots of reddish ink. On the solar disk, these defects look like artificial sunspots that are not easy to distinguish from real ones. Two drawings of 30 and 31 May 1703 are considered in Section 7, where they are compared with those by Hoffmann and Manfredi.

Figure 5a shows the observing note accompanying the drawing of 9 July 1703 saying that a major and a minor sunspot were observed on the Sun. An apparently bipolar sunspot group is sketched (marked by the red arrow). Similar mentions of the sunspots on 9 and

14 July 1703 were already shown by Hayakawa et al. (2021d, Figure 4 therein) among the other astronomical notes of Maria Eimmart and provided one sunspot group observed on 9, 14, and 16 July 1703.

Below, we consider the observations of Eimmart's contemporaries made in June and July 1703. With reference to la Hire, Spoerer (1889) wrote that there were no sunspots on 7 July, but there was a group on 8 – 16 July at −19° latitude. From drawings by Derham (1703) and Gray (1703), we estimate the latitude of a sunspot group to be between −20° to −25°. Also, Derham mentioned that the sunspot group of 8 – 17 July 1703 had "remarkable appearance and variations". This note suggests that Maria Eimmart's drawings depicted the location of sunspot groups schematically and not to scale.

Neuhäuser, Arlt, and Richter (2018) translated a letter by Kirch: "On [1703] July 8 another sunspot was found, in the other inch from the ingress [eastern] limb. On July 10 and 11 there were three [spots]. On July 15 we only could see one spot (through very thick air) at the egress [western] limb. The first spot did not come back on the ingress limb." They got a broad solution for sunspot latitude: $7 \pm 21°$. This leads us to an assumption of more than one sunspot group.

Returning to Maria Eimmart's drawing, it is posited that she may have rotated the paper as one would in a notebook. Consequently, in order to establish the coordinates of the sunspots, it is necessary to invert the drawings. In Figure 5, a reproduction of the sunspot drawing of 9 July 1703 is shown. The original image was made with gray and red pencils. The boundaries of the disks are slightly misaligned. Circles of digiti (in blue) and heliographic grid (in gray) are added by us. Taking an equatorial synodic speed rotation as $13.3°$ d^{-1}, we find that the red spot should have been about 2 inches from the eastern limb on 8 July and one inch from the western limb on 15 July, which is consistent with Kirch's description. There is also a gray spot, which Spörer and Derham marked as a group at −20° and one more at 10° in the northern hemisphere. As a result, we got three groups, which Kirch apparently mentioned on 10 and 11 July 1703.

7. Eustachio Manfredi, 28 May – 29 June 1703

Eustachio Manfredi, an observer based in Bologna, also reported on solar activity during May – June 1703. He made two images showing a sunspot transit. The drawings are stored in v. 4, f. 173 and are accompanied by a date, an observing time (hours after sunset of the previous day), sunspot position in arcminutes and arcseconds, and other information. The x-coordinates of the sunspots are scaled to the solar diameter of $2'16.5''$, while the y-coordinates are scaled to $31'42''$.

Figure 6 compares the original drawings by Manfredi and calculated sunspot positions according to micrometer measurements (red circles). Apart from the observation of 29 June 1703, drawings and tabular data are consistent. Similarly to Hoffmann, Manfredi has drawn sunspots not as they were seen in a telescope but already aligned. Therefore, we apply Method II to define sunspot latitudes. Also, following Hoffmann's speculation, we consider this series of observations as an activity nest living for several rotations. The corresponding Electronic Supplementary Materials contain the sunspot parameters reconstructed from both the drawings and micrometer measurements.

Figure 7 presents a comparison between the drawings by Hoffmann, Maria Eimmart, and Manfredi. It depicts the replicas of the drawings superimposed with the corrected orientation. Observing time is converted to UT. Hoffmann apparently depicted only sunspot umbre,
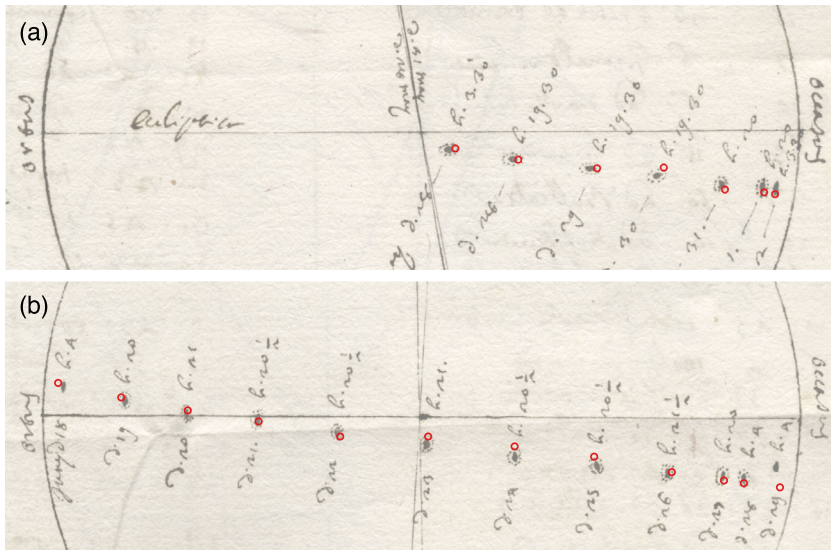
Figure 6 Superposition of sunspot drawings and tabular computations of sunspot position (*red circles*) made by Manfredi (Eimmart Archive Coll. 998, v. 4, f. 173).

while Maria Eimmart and Manfredi did not include small sunspots that accompanied the largest spot (Figure 4c). This leads to an underestimation of the sunspot-group area.

On 30 May, Maria Eimmart drew the sunspot in a uniform gray color, yet the next day the sunspot umbra was accompanied by an asymmetric penumbra. The observations by Eimmart also allow estimating the latitudinal uncertainty to be slightly greater than 3°. During $\approx$ 15 hours between these two observations, the longitudinal position of the spot decreased by 5.5°, implying that the associated longitudinal uncertainty is roughly twice that of the latitudinal uncertainty.

Manfredi apparently drew the penumbra and umbra schematically (Figure 7, blue). On average, the sunspot is located at $-1.7°$ in the southern hemisphere. Observations made by Manfredi from 28 May to 1 June yield the sunspot sidereal rotation period $14.3 \pm 1°$ d^{-1}, and $14.2 \pm 0.9°$ d^{-1} based on $20-28$ June 1703 (spots near the limbs were excluded from the calculations). These results are compatible with the equatorial velocity of about $14.5°$ d^{-1} derived by Balthasar, Vazquez, and Wöhl (1986) from the Greenwich Photo-heliographic Results. We believe that there are no misprints in the time of observation noted by Manfredi. Therefore, the observations by Hoffmann (Figure 7a, underlined red notes) of 29 and 30 May 1703 have been apparently made at 5 p.m. rather than at 5 a.m. The correction is further supported by the fact that the observation on the afternoon of 28 May is separated from the observation of 29 May by almost 13° in longitude, which corresponds to roughly 24 hours (red sunspots in Figure 7a). The first observation of 31 May should have also been made in the evening, and the next observation of that day likely corresponds to 1 June at $\approx$ 5 a.m. The note "1 Jun 5:36" is apparently the evening observation at 17:36, indicating a 12-hour shift in these records. In Figure 7b, the observation of 24 June was apparently made in the evening rather than in the morning hours. Once Hoffmann's time of observation is corrected, the velocity of the red sunspot transit from 26 May to 1 June 1703 equals $14.1 \pm 2.1°$ d^{-1}, and $14.5 \pm 3.1°$ d^{-1} from 20 to 28 June 1703.
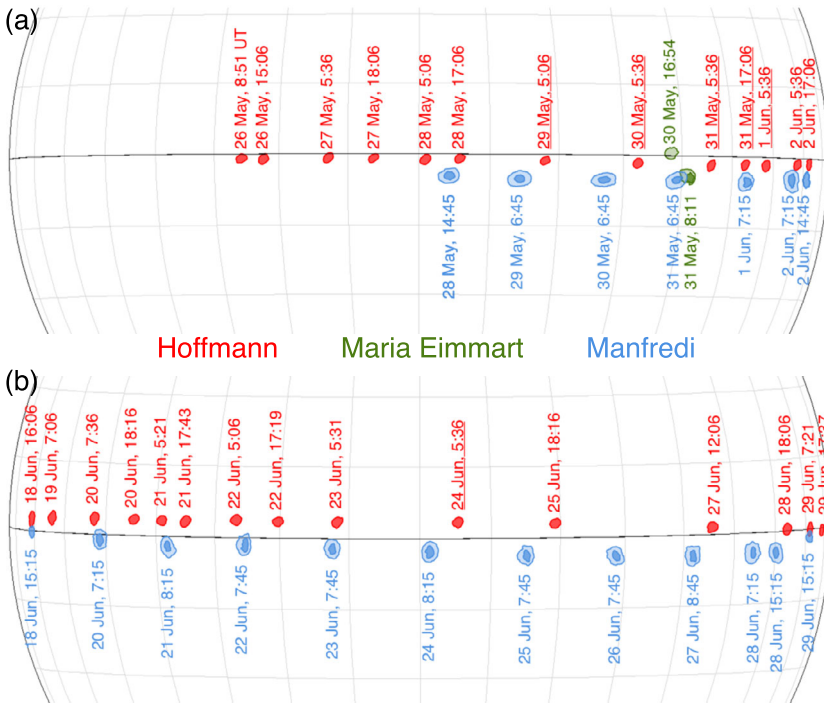
Figure 7 Superposition of sunspot drawing reproductions by Hoffmann, Maria Eimmart, and Manfredi from Eimmart Archive Coll. 998, v. 3, f. 423 – 424; v. 35, f. 38 – 39; and v. 4, f. 173, correspondingly. Heliographic grids correspond to 26 May (**a**) and 18 June 1703 (**b**) seen at the Eimmart Observatory. Observing times reported by the observers are given in UT. Underlined notes suggest instances of probable time imprint.

8. Johann Heinrich Müller, 9 – 14 October 1705

A drawing by Müller stored in v. 35, f. 57 was made with both pencil and ink. It depicts sunspots labeled as *a*, *b*, *c*, and a chain of sunspots labeled as *d-d-d* (in Latin: *maculae tres d,d,d, vinculo quasi cunctae observatae...*) along with the corresponding time of observation (Figure 8 Left). Here, we exploit only Method I due to limited observations.

At first sight, the location of the east and west limbs suggests that the image should be flipped horizontally from right to left, as shown in Figure 8 Top. Sunspot latitudes vary in the range of $15 - 20°$, while longitudes differ significantly. This indicates that either the sunspots belong to four different groups, or the initial assumption of flipping the image horizontally is incorrect. We lean towards the latter assumption. Therefore, we also examined the original orientation of the image and a version rotated by 180°. However, in both cases, sunspot latitudes and longitudes exhibited significant changes, indicating that these orientations are also incorrect.

Another possibility is that the drawing was flipped vertically, as shown in Figure 8 Bottom. The longitudes and latitudes of the sunspots *a*, *b*, and *c* on 9 and 10 October (highlighted in red) remain consistent, indicating that they belong to the same sunspot group. The sunspot chain labeled as *d-d-d* on 14 October (in blue) appears to belong to another group. Although the results following from this interpretation are the most consistent, the image designations of East and West would then be incorrect.
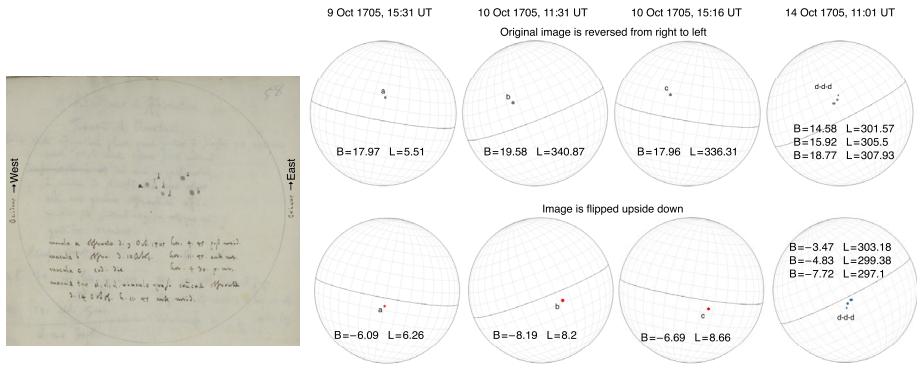
Figure 8 (*Left*) Original sunspot drawing by Müller (Eimmart Archive Coll. 998, v. 35, f. 57). (*Top*) Reproduction of the drawing flipped horizontally; (*Bottom*) vertically. Heliographic grids are found for the observing time Müller noted. Latitude *B* and longitude *L* of sunspots are listed.

Spoerer ([1889](#)) did not include the exact sunspot latitude. However, he wrote that on 4 October 1705, there were eastern sunspots (östlich Flecke) that had already moved to the western part of the disk by 12 October. This description matches the transit of sunspot groups *a*, *b*, and *c*. Further, Spoerer noted that on that day (12 October) new sunspots came from the East, which he considered a "rare case" (quotation marks by Spörer). This simultaneous appearance of sunspots in distant regions of the Sun had only been observed once before, in January 1704, following Scheiner's observations.

Neuhäuser, Arlt, and Richter ([2018](#)) translated a letter by Kirch: "This afternoon [1705 Oct 16] around 2:30 h, we got to see two fine spots in the Sun, about 3 inches from the egress edge." and a letter by Wurzelbaur "...in the last October [1705], when two [sunspots] did not have fully crossed the solar disc, when two other spots with an accompaniment entered the disc." They determined the latitude of the spots ranged from −13.9° to 23.3°. This is consistent with the position of the sunspot chain *d-d-d* (Figure [8](#) Bottom), which should be located about 3 inches from the western limb toward 16 October.

Based on the analysis presented above, we suggest sunspot groups *a*, *b*, *c*, and *d-d-d* were simultaneously present on the visible disk of the Sun for several days between 10 and 14 October. Müller's original drawing depicts the upside-down image of the Sun with an east-west orientation that is consistent with that of the Sun, but with an incorrect E–W annotation. A similar conclusion was obtained by Hayakawa et al. ([2021d](#)) who evaluated the sunspot groups' latitudes to be about −5° and −8°, while our analysis suggests a latitude of approximately −7°.

9. Johann Heinrich Müller, 14 December 1706

Another drawing by Müller is stored in v. 36, f. 19. The text description (Figure [9](#) Left) says that sunspots were observed in Nürnberg on 14 December 1706 at Noon and the smallest sunspot was barely visible near the circumference (In Latin: Macula minima ad modum...). The cardinal directions are also indicated, West and East are opposite to the solar ones. In the corner of the original drawing, Müller wrote: "D. 2[?] Dec. mac. dispar." This might be interpreted as sunspot(s) disappearing on 2[?] December. The inscription is faint, and it looks like something is written behind the 2, possibly indicating 21 or 22 December. This
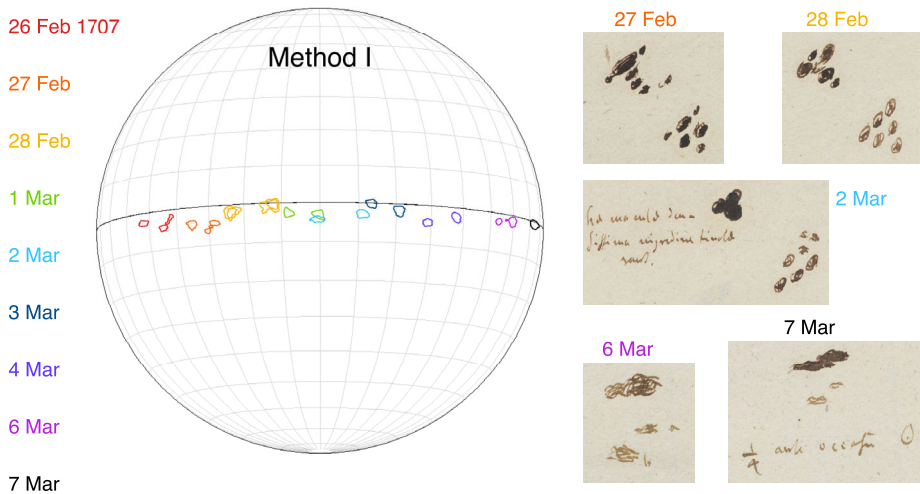
Figure 9 (*Left*) Original sunspot drawing by Müller (Eimmart Archive Coll. 998, v. 36, f. 19). The inscription in the *lower-right corner* is enlarged. (*Right*) The reproduction of the original drawing that was flipped vertically (*in red*). The heliographic grid corresponds to the time of observation noted by Müller. *Pink and dark red* denote the positions of the largest sunspot calculated for 13 and 16 December 1706.

interpretation would make sense with the small spot on the left side of the drawing. The term "disparare" can mean to separate or divide, but it may also carry the sense of dissolve. Given that the spot should still have been visible on the disk, it is possible that it had split or dissolved.

Similar to Section 8, we considered four image orientations and chose the most probable one that yields consistent sunspot positions. As displayed in Figure 9 Right, the drawing is flipped upside down (red spots), and the heliographic grid corresponds to UT time of the local Noon. Here, we assign two sunspot groups.

Neuhäuser, Arlt, and Richter (2018) analyzed letters by Kirch and his wife. Maria Kirch reported the distance of the largest sunspot to the limbs on 13 December 1706 before Noon, at around 11:30 local time. We suggest that the sunspot location measurements were made on a line parallel to the celestial Equator. Thus, the possible position of the largest sunspot on 13 December is shown in pink (Figure 9 Left). On the other hand, Gottfried Kirch reported that on 16 December 1706, before noon, the large spot was 1/2 inch from the western limb. A possible location of the sunspot is shown in dark red. The resulting sunspot track is consistent with the solar-rotation rate, and the derived sunspot latitudes are in agreement with those obtained by Hayakawa et al. (2021d).

10. Johann Heinrich Müller, 26 February – 7 March 1707

A collection of drawings produced by Müller between 26 February and 7 March 1707 is stored in v. 36, f. 107–116. They were drawn with both ink and pencil and accompanied by a day and a time. On nine separate drawings, the spots of an individual day are shown. An additional drawing exhibits the passage of sunspots on the solar disk throughout the entire observation period.

Images were reversed vertically. Figure 10 Left shows sunspot positions derived by Method I. On 28 February 1707, sunspots were drawn with a pencil and overlaid with ink. Hence, there are two sunspot contours on this day. On the back of the folios, Müller also

Figure 10 (*Left*) Sunspot positions derived by Method I. Days are color-coded. (*Right*) Detailed drawings of sunspots from Eimmart Archive Coll. 998, v. 36, f. 107 – 116.

sketched sunspots in more detail (Figure 10 Right). Therefore, sunspot areas derived from Müller's drawings of the whole solar disk and presented in the corresponding Electronic Supplementary Materials, may not accurately reflect the actual size.

Neuhäuser, Arlt, and Richter (2018) calculated the most probable latitude for the sunspot to be $-3.5 \pm 27°$, which is in agreement with the value provided by Hayakawa et al. (2021d). Spoerer (1889) also provided a similar estimate of $-6°$ for the sunspot latitude. From nine separate drawings, our analysis using Method I yielded an average sunspot latitude of $-2.5 \pm 1.5°$, while Method II yielded an average of $-3.6 \pm 0.4°$. Moreover, from the drawing showing the passage of sunspots on the disk for all days, the estimated latitude is $-3.2 \pm 0.7°$ using Method I and $-5.8 \pm 0.5°$ using Method II.

11. Johann Heinrich Müller, 12 August – 18 November 1708

Three similar sunspot drawings of 12 August – 5 September 1708 with different orientations provided by Müller are stored in v. 36, f. 136 – 137. One of the drawings is shown in Figure 11a, where sunspots from 12 to 17 August are marked with letters. Also, two sunspots on 4 and 5 September 1708 appeared on the same line. Similar to the previous observations, cardinal directions are opposite to the solar ones. On the back of one of the drawings, three sunspot groups are shown in detail on 15 August and 5 September (Figure 11b). It follows that Müller sketched only the largest sunspot of a group passing on the solar disk.

The handwritten text is hard to make out, but the meaning of the note is probably the following. Toward 15 August, the sunspot labeled as *a* became weak; on 16 and 17 August, only the sunspot labeled as *b* could be seen in the helioscope. The same sunspot returned on 4 and 5 September and was seen until 14 September 1708, the day of the solar eclipse.

Figure 11c shows a colored replica of three original drawings. As can be seen, the sunspot locations do not always match. The largest discrepancies are shown by small arrows. The corresponding Electronic Supplementary Materials provide data for all three drawings. Since Müller did not report the time of observation, only Method II was applied, giving a
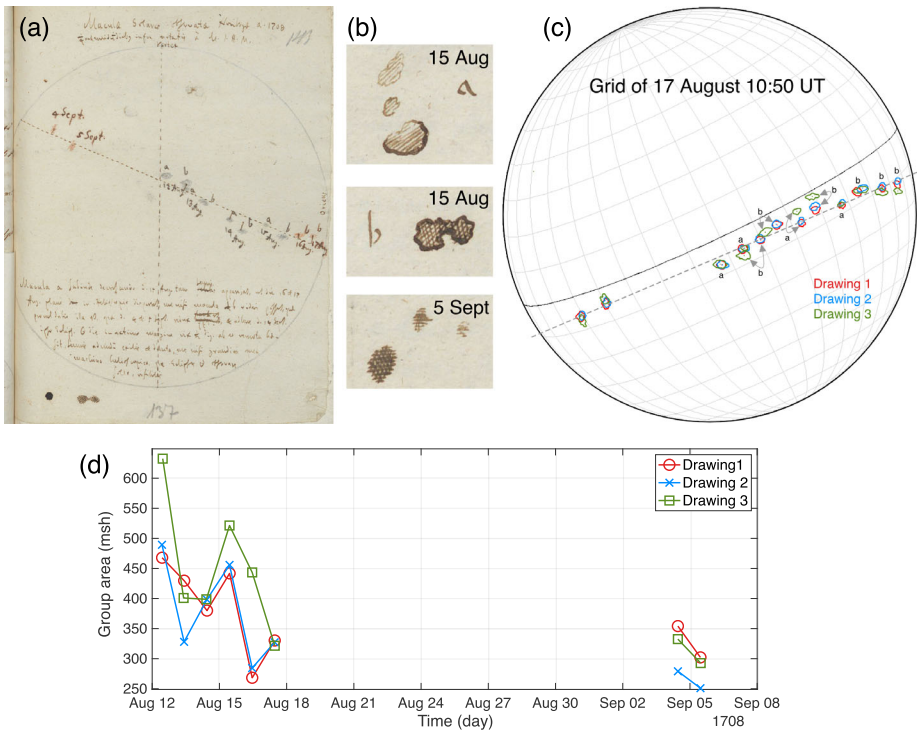
Figure 11 (**a**) One of the original drawings of sunspot transit from 12 August to 5 September 1708 by Müller (Eimmart Archive Coll. 998, v. 36, f. 136 – 137). Sunspots are marked with letters. (**b**) Detailed drawings of sunspots. (**c**) A colored reproduction of three original drawings. *The largest discrepancies in sunspot position are shown by arrows.* The heliographic grid corresponds to 17 August 1708. (**d**) Sunspot-group areas derived from the three drawings.

sunspot latitude of $6 - 7°$ in the southern hemisphere. Referring to Wideburg, Spoerer (1889) gave a latitude of $-7°$ for $11 - 18$ August and $-5°$ for $2 - 14$ September 1708. Reconstructing sunspot positions from letters by Kirch, Neuhäuser, Arlt, and Richter (2018) yielded $8.9 \pm 10.5°$ for $10 - 18$ August and $-2°$ for 14 September 1708.

Figure 11d compares sunspot-group areas derived from three drawings. The results indicate that the average uncertainty of sunspot area measurement is approximately 30%, consistent with our previous estimations (Vokhmyanin, Arlt, and Zolotova, 2021).

The next drawing by Müller, made with a pencil on 17 and 18 November 1708, is stored in v. 36, f. 138. Similar to Müller's previous observations, we reversed the images vertically. The time of observation is unknown. We combined pairs of observations by Müller and Wideburg (1709) to make the results more reliable (Figure 12a). Note that Wideburg sketched the penumbra and umbra. The relative size of the spots drawn by Müller suggests that the boundary of his spots corresponds to the outer boundary of the penumbra. Figure 12b shows the passage of the sunspot according to Method II, which placed sunspots slightly below the Equator with an average latitude of $-1.3 \pm 0.02°$. Referring to Wideburg, Spoerer (1889) gives $-4°$ on $14 - 21$ November 1708. However, due to poor statistics and uncertainties, the observed sunspot on 17 and 18 November 1708 may potentially belong to the northern hemisphere. For instance, Hayakawa et al. (2021d) have suggested that the sunspot may have indeed been located in the northern hemisphere.
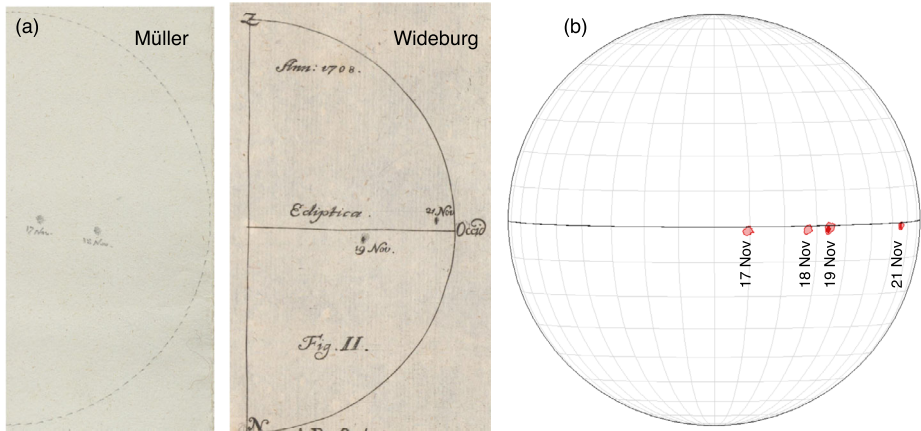
Figure 12 (**a**) Original drawings of 17 and 18 November 1708 made by Müller (Eimmart Archive Coll. 998, v. 36, f. 138) and of 19 and 21 November 1708 made by Wideburg (1709); (**b**) sunspot positions as derived by Method II.
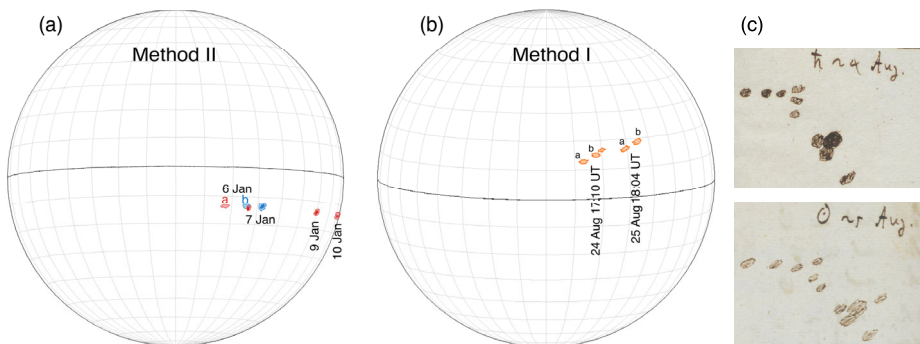
Figure 13 (**a**) Sunspot positions derived by Method II using the observations made by Müller on 6 January 1709 (Eimmart Archive Coll. 998, v. 36, f. 153) and by Wideburg (1709) on 7 – 10 January. Sunspots labeled *a* and *b* are shown in colors. (**b**) Sunspot positions derived by Method I from the observations made by Müller on 24 and 25 August 1709 (Eimmart Archive Coll. 998, v. 36, f. 154) and (**c**) the corresponding detailed drawings for each day.

12. Johann Heinrich Müller, 6 January, and 24 – 25 August 1709

Two observations, one on 6 January and another on 24 – 25 August, are available in v. 36, f. 151 – 154. In the winter drawing, sunspots are marked with letters *a* and *b*. We supplemented this observation with the drawings made by Wideburg (1709) on 7 – 10 January. Figure 13a shows sunspot positions restored by Method II.

Analyzing reports from 5 – 9 January 1709 by Peter Becker, Neuhäuser et al. (2015) concluded that the latitudes of two sunspots varied from -9 to $-15°$, while the longitudes were between $223 - 231°$. This is close to our estimates ($-14 \pm 0.2°$ latitude, $231.6 \pm 3°$ longitude). Hayakawa et al. (2021d) gave latitudes closer to $-20°$, and Spoerer (1889) reported $-16°$.
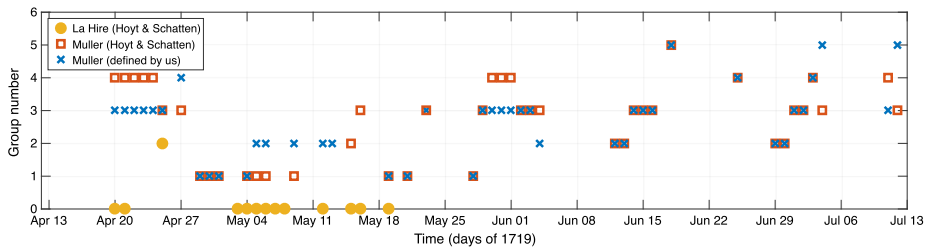
Figure 14 Group number defined from Müller's and La Hire's observations by Hoyt and Schatten (1998) and in this work.

For the August observations, Müller noted the time of observation. Figure 13b shows the sunspot positions derived by Method I. Sunspots were found to occupy the $13-18°$ band of latitudes. Hayakawa et al. (2021d) evaluated the latitude to be about 10°, Neuhäuser, Arlt, and Richter (2018) yielded 6°, while Spoerer (1889) provided a latitude of $-7°$ for $25-27$ August 1709.

In the comments to the observations on 24 and 25 August, Müller also sketched the sunspot group in more detail. The sunspot group consisted of multiple sunspots as can be seen in Figure 13c. In contrast, his drawing shown in Figure 13b marks only two sunspots *a* and *b*, indicating a more schematic representation. This suggests that sunspot drawings during that time may have varied in their level of detail and accuracy.

13. Johann Christoph Müller, 20 April 1719 – 27 May 1720

An album containing solar-disk drawings by Johann Christoph Müller (Johannes Christophorus in Latin transcription), the brother of Johann Heinrich Müller, is stored in v. 56. As listed in the catalog, the drawings were made in ink, watercolors, brush, and pen and are accompanied by dates and times. Recently, Hayakawa et al. (2021b) analyzed this archive, extracting the number of sunspots, sunspot groups, and their positions. They also provided a review of Müller's observational equipment.

In comparison with Hayakawa et al. (2021b), we assigned the same number of sunspot groups. However, we have made two slight differences in our analysis on 4 May and 2 June 1719. Specifically, we have ignored two small objects on these dates, which differ in color from the other sunspots and rather appear to be paper defects. Figure 14 shows sunspot-group numbers assigned by Hoyt and Schatten (1998) and our analysis of Müller's album. Apart from very few discrepancies, the number of groups is generally consistent with our results. In addition, we have also included the group numbers from the observations by La Hire in yellow. In the references, Hoyt and Schatten noted that the primary source of the La Hire observations was the re-examination of original notebooks made by Elizabeth Nesme-Ribes. As an example of the fine structure of a sunspot, the La Hire drawings were examined by Ribes and Nesme-Ribes (1993, Figure 1 therein) who suggested that sunspots as large as one arcsecond could not have been missed by Parisian telescopes.

We suggest that La Hire's reports may not have been sunspot observations but rather were made for different purposes. This is similar to the case of Georg Christoph Eimmart's solar-altitude measurements, which should not be confused with reports on a spotless solar disk (Hayakawa et al., 2021d). Out of the 13 observations made by La Hire, 8 overlap with those by Müller, and on 12 of those days, Müller reported sunspot groups with areas ranging from 33 msh to 871 msh based on our measurements.
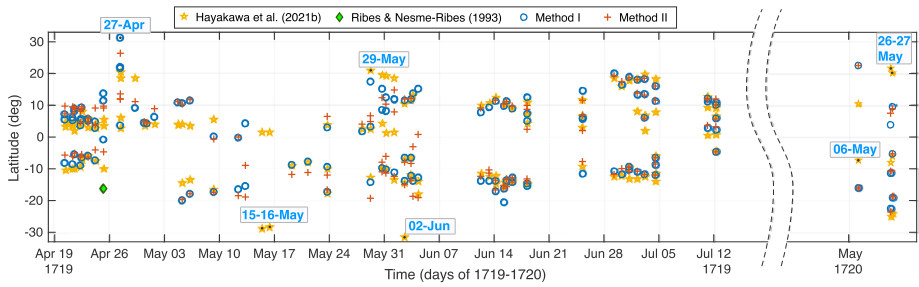
Figure 15 Time–latitude diagram of Müller's reports reconstructed by Hayakawa et al. (2021b) and in Methods I and II. *Green diamond* is La Hire's observation.
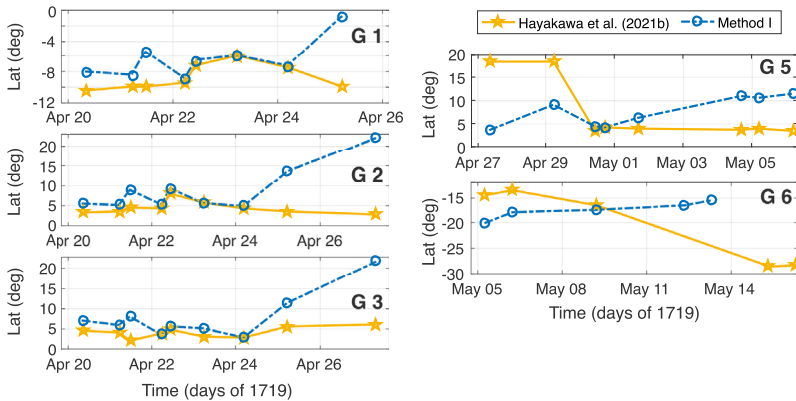

Figure 16 Latitudes of sunspot groups G1 – G6 defined by Hayakawa et al. (2021b) and using Method I.

Figure 15 compares the spatio-temporal distribution of sunspot groups defined by Hayakawa et al. (2021b) in Methods I and II and one Parisian observation. As the notebooks by Elizabeth Nesme-Ribes are lost, Vaquero, Nogales, and Sánchez-Bajo (2015) provided a machine-readable version of the Ribes and Nesme-Ribes (1993, Figure 6 therein) butterfly diagram. The only point overlapping in time with the Müller's observations is about 22 April (or 1719.30771, as expressed in a fraction of year), $-16.2°$ of latitude. Compared to the Hoyt and Schatten (1998) findings, this observation was apparently made by La Hire on 25 April 1719 (green diamond in Figure 15). In April, Müller reported one sunspot group in the southern hemisphere above $-10°$ with a maximal area of 71 msh. Hence, both La Hire and Müller had equipment capable of resolving the fine structure of sunspots, but did not report all objects present on the solar disk. There may be other reasons for this discrepancy.

The mean latitude discrepancy between latitudes defined by Hayakawa et al. (2021b) and the two methods is about $3°$, i.e. within the uncertainty range. However, on several days the difference significantly increases (marked in blue in Figure 15).

Figure 16 compares latitudes of sunspot groups G1 – G6 in our numbering (G4 is a one-day-lifetime sunspot at $31°$, not shown). The dashed blue curve represents the latitudes derived by Method I in accordance with the time noted by Müller. On 20 – 24 April 1719, Hayakawa et al. (2021b) apparently minimized the latitude scatter of sunspots also around the time noted by Müller (yellow and blue curves are close). On 25 and 27 April, latitudes of groups G1 – G3 significantly rise (in blue). One may suggest that either Müller indicated the
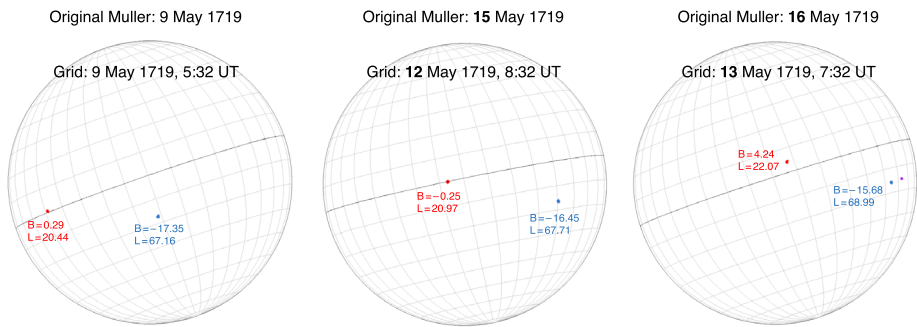
Figure 17 Reproductions of the three consecutive drawings made by Müller from 9 May to 16 May 1719 (Eimmart Archive Coll. 998, v. 56, f. 11–12). Latitudes and longitudes of the sunspots are indicated with letters *B* and *L*.

wrong time or incorrectly drew the position of the sunspots. In Hayakawa et al. (2021b), the heliographic grid was rotated inconsistently with the time noted by Müller. Consequently, in the next few days, the scatter of groups G5 and G6 has risen (Figure 16).

Figure 17 reproduces three consecutive drawings originally signed by Müller as observations on 9, 15, and 16 May 1719. The longitude distance between the red and blue sunspots (which we have numbered as S14 and S15, respectively, as shown in the corresponding Electronic Supplementary Materials) equals 46° on each of the three days. Therefore, we hypothesize that these are the same sunspots. However, the rotational matching analysis states that on 15–16 May, the sunspots should have been much closer to the western limb. If we assume that there was a typographical error in the date of the first observation (9 May), it would break the coherence of sunspot latitudes and longitudes in the days prior to 9 May. Eventually, we suggest that the observations originally labeled as 15 and 16 May are actually the observations of 12 and 13 May 1719. The improved heliographic grids defined by means of Method I and sunspot coordinates are shown in Figure 17. On the contrary, it could also be argued that the sunspots observed on 9 May decayed, and new objects emerged on 15 May. Both Hoyt and Schatten (1998) and Hayakawa et al. (2021b) provide the observation dates as originally noted by Müller, which affects the reconstructed longitudes.

On 29 May – 1 June 1719 (Figure 15) the latitudes defined by Hayakawa et al. (2021b) significantly deviate from results by Method I. Such a difference suggests that the sunspot positions defined by Hayakawa et al. (2021b) are less consistent with what should have been seen in the telescope. We also ignore the sunspot on 2 June 1719 at $-31.5°$. It has a different color compared to other sunspots, and we believe this is rather a paper defect.

The reproduced images of five consecutive drawings of 1–4 June 1719 are shown in Figure 18. For similar reason as in Figure 17, we believe that Müller observed the transit of the same sunspots marked in blue and red (S34 and S36 in the Electronic Supplementary Materials) during these four days. We imposed four grids of 1–3 June reconstructed by Method I on a reproduction of the original images, while a grid of 4 June was imposed on the vertically flipped image. Utilizing the original image, the latitudes of sunspots on 4 June deviate from their means on 1–3 June as much as 25–30°. However, if we flip the image, the difference reduces to only 3°. It is possible that Müller rectified the original images viewed on a projection screen but forgot to do so on 4 June. Hayakawa et al. (2021b) used the original orientation of the drawing of 4 June 1719 with a grid orientation different from the one indicated by Müller's time note.
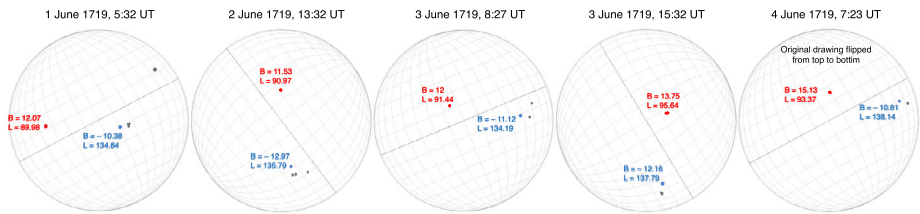
Figure 18 Reproductions of the five consecutive drawings made by Müller on 1–4 June 1719 (Eimmart Archive Coll. 998, v. 56, f. 16–18). Latitudes and longitudes of the sunspots are indicated with letters *B* and *L*.
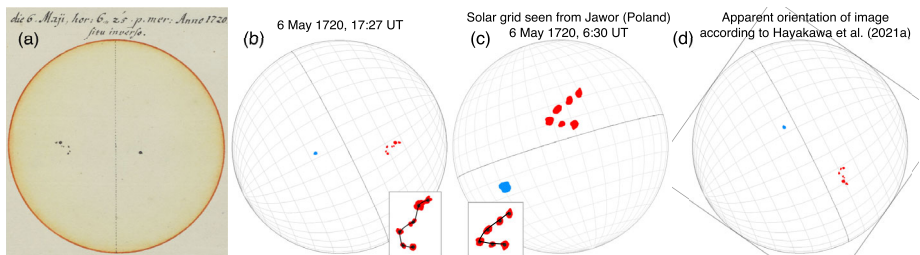

Figure 19 (**a**) Original drawing by Müller (Eimmart Archive Coll. 998, v. 56, f. 26). (**b**) Reproduction of the drawing reflected from right to left with heliographic grid according to time of observation noted by Müller. (**c**) Reproduction of sunspot drawing from Kanold (1721) and the heliographic grid as it was seen from Jawor (Poland). (**d**) Apparent orientation of the image according to Hayakawa et al. (2021b).

Another difference in the spatio-temporal distributions is seen in the observations made on 6 May 1720. According to the original note, the drawing was reversed, or "situ inverso" (Figure 19a). To find a suitable orientation of the image, we followed the approach used by Hayakawa et al. (2021b) and referred to the drawings by Alischer, published by Kanold (1721). Figures 19b and c compare a reproduction of Müller's horizontally reversed drawing and Alischer's drawing, showing sunspot groups in different colors. We selected the proposed reversal of the Müller's drawing because the orientations of a large sunspot group reported by Müller and Alischer were similar, with four sunspots directed toward high latitudes and a smaller number toward the Equator (as seen in the sunspot skeletons in the small rectangles). However, groups in the Müller's drawings are located further West than in Alischer's version. Notice that the following day, Alischer shifted sunspots about 30° to the western limb. Figure 19d shows the apparent orientation of the image chosen by Hayakawa et al. (2021b), where the original image is rotated 145° counterclockwise.

Finally, on 26–27 May 1720, Methods I and II provide similar results, i.e. consistent with the time noted by the observer. Hayakawa et al. (2021b), on the other hand, substantially rotated the grid counterclockwise.

14. Conclusion

We study sunspot drawings from 1616 to 1720 made by historical researchers, whose observations are collected in Eimmart's archive stored in the National Library of Russia in St. Petersburg. Cumulatively, we processed 551 objects on 109 drawings of the solar disk

reported by seven observers. We assigned 177 sunspots, which were sorted into 67 groups according to the classification by McIntosh (1990). Area (umbra and penumbra, if available) and heliographic position were derived for each object. Results are compared with data provided by the other observers – contemporary observers of the Maunder minimum.

A notable difference between the observations by Saxonius is the number of sunspot groups defined by Hoyt and Schatten (1998) and the present study. Apparently, Hoyt and Schatten assigned groups in accordance with Saxonius's lettering.

To assess the uncertainty in sunspot position due to observation technique and subsequent drawing and redrawing, three copies of the sunspot transit from $2-8$ July 1684, reported by Georg Eimmart, were compared. The average uncertainty in both latitude and longitude was found to be $3-4°$. The derived latitude and longitude of the sunspot groups match those from observations of 11 and 12 June 1684 by Wurzelbau. While historical observers hypothesized that this sunspot group had lived for four solar rotations, it is more likely that they have reported on a complex activity nest.

The drawings from 26 May to 16 July 1703 by Hoffmann and Manfredi reveal that the observations were aimed at tracing the reappearance of sunspots on the next rotation. Hoffmann did not draw sunspot penumbra, while Manfredi did not draw small sunspots accompanying the major sunspot of the group, which resulted in an apparent underestimation of the area.

Our previous estimation of the average uncertainty of sunspot-area drawing, which is roughly 30%, is supported by three copies of a sunspot report made by Müller in 1708. Moreover, detailed drawings of sunspot groups in $1707-1709$ on the back of the manuscript sheets with solar-disk drawings reveal that groups could have had a complex structure, which hints at a greater under-estimation of the derived areas compared to their actual sizes.

Comparison of the observations by La Hire and Müller in $1719-1720$ uncover that group numbers extracted from La Hire's reports are usually zero, while Müller's album depicts sunspot groups from 33 to 871 msh. We suggest that the observations by La Hire were primarily for astrometric purposes like solar-altitude and solar-diameter measurements rather than aimed at counting sunspots.

Sunspot-group positions given by Hayakawa et al. (2021b,d) and in this work are usually similar. However, discrepancies are discussed, which result from different approaches to minimizing sunspot-latitude scatter. To deduce sunspot coordinates, we use two methods: Method I is based on the observation time, while Method II provides average sunspot latitudes, which may be useful when sunspot latitudes significantly vary from day to day. If sunspot coordinates were calculated by both methods for a series of observations (see Electronic Supplementary Materials), we recommend using latitudes from Method II and longitudes from Method I. For the benefit of an open discussion, the processed drawings will be available at geo.phys.spbu.ru/~ned/History.html.

Declarations

Competing interests   The authors declare no competing interests.

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