DIGITIZATION OF SUNSPOT DRAWINGS BY STAUDACHER IN 1749–1796

R. ARLT
Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany (rarlt@aip.de)

Received ; accepted

Abstract. Original drawings by J.C. Staudacher made in the period of 1749–1796 were digitized. The drawings provide information about the size of the sunspots and are therefore useful for analyses sensitive to the sunspot area rather than Wolf numbers. The total sunspot area as a function of time is shown for the observing period. The sunspot areas measured do not support the proposition of a weak, "lost" cycle between cycles 4 and 5. We also evaluate the usefulness of the drawings for the determination of the positions of the sunspots for future studies.

Keywords: Sun: sunspots, Sun: magnetic field

1. Introduction

Solar activity is often expressed by various quantities derived from the appearance of sunspots. The Wolf sunspot number is one of them and can be constructed for observations since 1700 (Waldmeier 1960). Another quantity is the group sunspot number introduced by Hoyt and Schatten (1998) which allows for more observations to be included in the time series, then going back to 1610. While these numbers show the activity cycle of the Sun quite precisely, it is desirable to obtain sunspot areas and positions over a long time span, too. These have hitherto been available since 1874 with the Greenwich solar drawings.

A considerable amount of observations contributing to the Wolf/group sunspot numbers of 1749–1796 were made by the amateur astronomer Johann Caspar Staudacher. The drawings are stored in the library of the Astrophysikalisches Institut Potsdam, Germany, and are in very good constitution. We present the results of the digitization of the sunspot drawings by Staudacher (baptized 1731 January 6, year of death unknown) who observed from Nuremberg, Bavaria. His name was sometimes spelled Staudach by himself. The present Paper elucidates the drawing styles and the scientific usefulness of the sketches. It also reports sunspot areas for the entire period. The measurement of individual spot positions will be presented in a future article.

The drawings cover the period of 1749 February 15 to 1796 January 31. The typical layout of the book is shown in Figure 1. A total of 848 hand-made

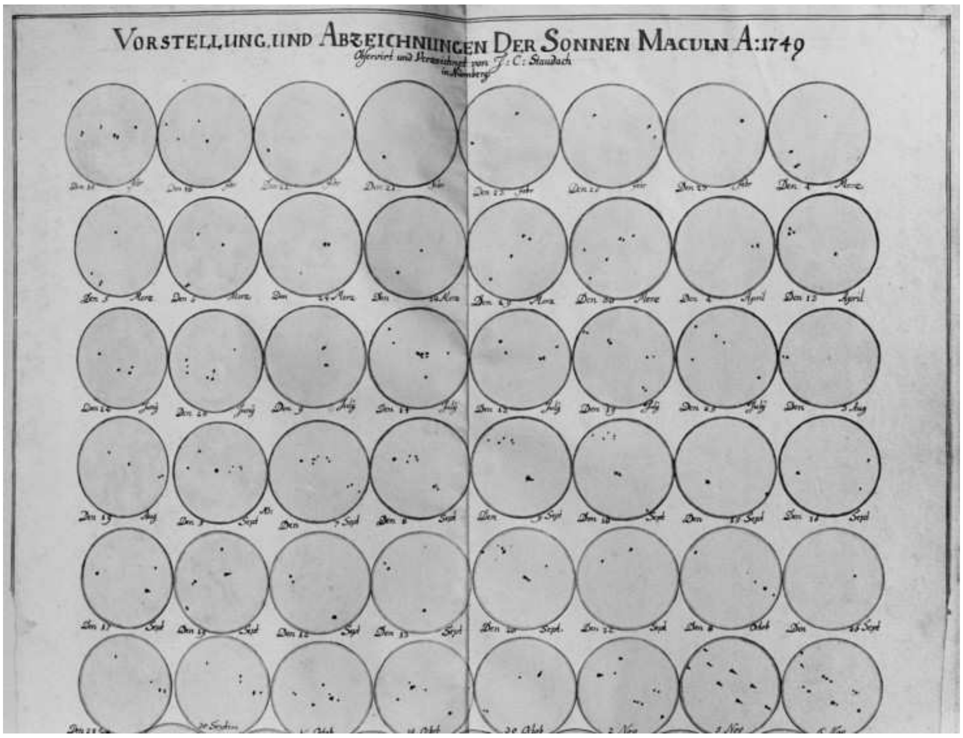

Figure 1. Overview of the first page of the Staudacher drawings. The actual images for the digitization were taken at a larger scale.

sunspot drawings or verbal text fields are found in the book plus additional drawings of solar and lunar eclipses, transits of Venus and Mercury, and geographical drawings. The total number of days for which the positions of sunspots are given is 1016, including dates without any sunspots seen. Two or more observations were often combined in one drawing. The distribution of observations over the entire observing period is very uneven and varies from none in 1755 to 117 in 1762 (Figure 2). The average is 21 observations per year. The distribution has a number of maxima which is correlated with the maxima of solar activity only very loosely. Staudacher's motivation to make solar observations was obviously not stimulated by solar activity maxima. Also central European weather alone does not lead to such an uneven distribution.

We have almost no information on the telescope Staudacher used. There is a single mention of a telescope on 1775 February 18 during the observation of an occultation of Saturn by the Moon, when Staudacher wrote: *"... als ich mich darauf umsahe mit meinem 3 Schuhigten himmels tubus, so stund ♄ ganz genau am finsteren ☾ rand"* (... when I turned round with my 3-foot sky tube, there was Saturn exactly at the dark rim of the Moon). The length of the foot unit was 30.4 cm in Nuremberg; we may assume that the focal length of the telescope was about 91 cm.

Achromatic telescopes with a focal length of 92 cm were in fact manufactured by John and Peter Dollond starting their business in the late 1750s (King 1955). These telescopes also arrived in Germany, since we know that the astronomer Iohann Hieronymus Schroeter had used one of them for solar observations since 1779 (Schroeter 1789). With such a telescope, however, the distinction between umbra and penumbra should have been possible, and the Wilson effect should have been visible. Both were not noted by Staudacher, except for a few occasions when the drawings give the impression of a dark core embedded in a penumbra, but these may simply be an effect of the water colour he used, since the occasions are rare, and there are "penumbrae" without "umbrae" (Figure 3). Wilson made his observations of the depression effect with a clear distinction of umbra and penumbra with a Gregorian telescope with 66 cm focal length, smaller than what Staudacher mentions. Wilson (1774) describes the telescope as being "excellent"; an average Gregorian used by an amateur probably suffered from fairly strong spherical aberration at the time. Because of a couple of mirrored solar-eclipse drawings, we suggest that Staudacher was using a Keplerian refractor with a non-achromatic objective.

2. The digitization

Since it is not wise to expose the drawings to bright light, we decided to take photographic images of the book. As there is no limitation on the exposure time, the book could be photographed in the relatively dim, ambient light of the room where it is stored. It was subject to very mild mechanical handling, actually none apart from turning the pages. Scanning would have meant much more severe mechanical suffering.

The photographic device was a digital single-lens reflex camera Canon 350D (Digital Rebel XT on the US market). The camera has an 8-megapixel CMOS sensor which provided enough resolution for the purpose described here. The focal length was between 110 and 120 mm for the images. The exposure was 1/3 second at apertures of $f/8$ to $f/10$. The analog-to-digital conversion was done at an equivalent sensitivity of ISO 100. The images in JEPG format produced by the camera were considered of sufficient quality for this purpose. A conversion of the full raw sensor information as provided by the camera was not necessary.

The size of the drawings of the solar disk varied such that either four or six drawings were captured in one digital image. The images were cropped to individual drawings, one image file for each day the Sun was observed. A

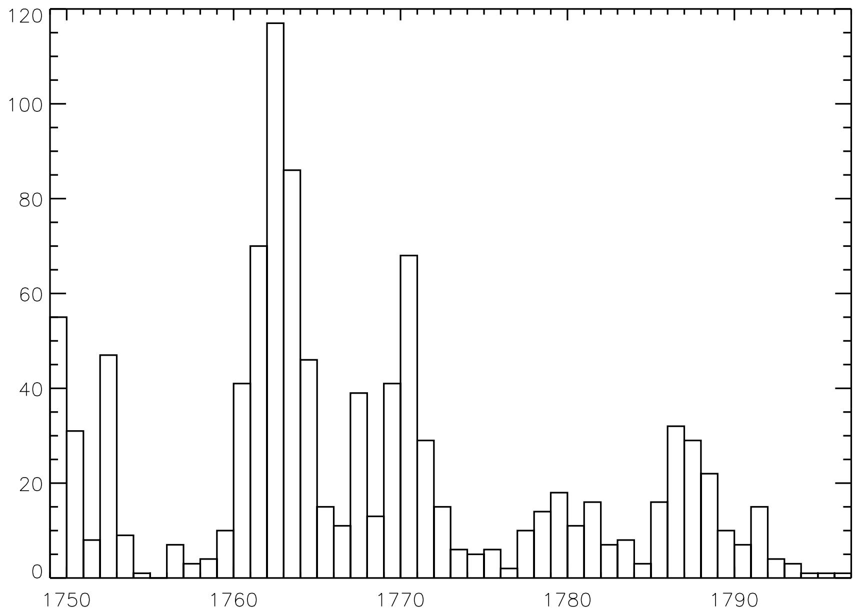

Figure 2. Distribution of observations by Staudacher for the years 1749–1796.

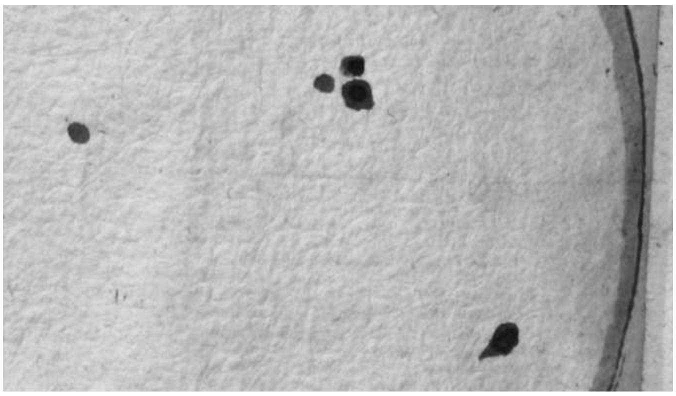

Figure 3. Part of the drawing of 1761 June 5 with indications of penumbrae. The appearance is, however, likely to be an effect of the water colour Staudacher used.

number of images contained the sunspot information of two or more days. Identical files were created with different file names, the analysis described below in Section 5 was adapted accordingly. The final solar disks have diameters between 680 and 1100 pixels. The geometrical resolution is thus at worst 2.6″ which is supposed to be higher than the drawing precision by Staudacher.

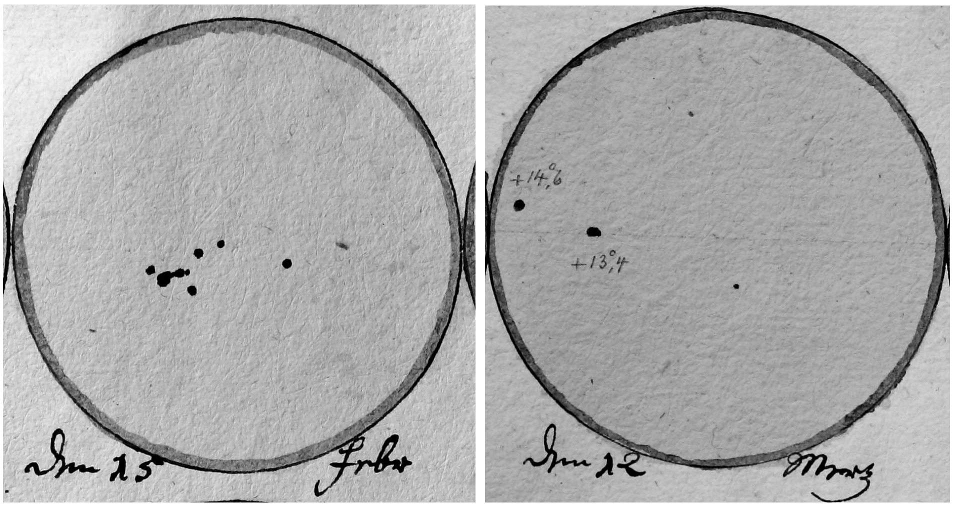

Figure 4. Drawing of 1760 February 15 (left) as an example of a typical representation of the spot distribution. Drawing of 1752 March 12 (right) with annotations in degrees which are probably not due to Staudacher but were added later.

3. The individual sunspot drawings

Dates may have been given in the old astronomical style occasionally, i.e. the day starts at noon, not at midnight. For example, the solar eclipse on 1769 June 4, has been drawn for 1769 June 3, because it was in the morning hours. However, the earlier eclipse of 1753 October 26 was also in the morning hours, but still noted as being on October 26. Perhaps one of the two was a typo, or Staudacher learnt about astronomical dates after 1753, when he was about 24 years old, and started using them since. For most applications, the uncertainty in the date definition has a negligible effect.

Staudacher drew his solar images with black ink. The solar disk was painted with yellow water colour until 1768 February 17. The remaining images were not coloured. Concentric circles, obviously representing 15°-steps were added starting in January 1764. A number of drawings (14 out of 40) of 1769 have no such circles though.

A difficult issue is the accuracy or level of detail of the drawings. The left panel of Figure 4 shows a typical image of the solar disk with a few single spots and a group of medium size. Nearly all of the spots show no distinction of umbra and penumbra. The size of the ink spots indicates that Staudacher included the penumbra in the spot size. He had certainly difficulties in separating them with his amateur telescope of the time. If he could not, he most likely missed all the A and B spot groups (referring to the Waldmeier classification, Waldmeier 1938).

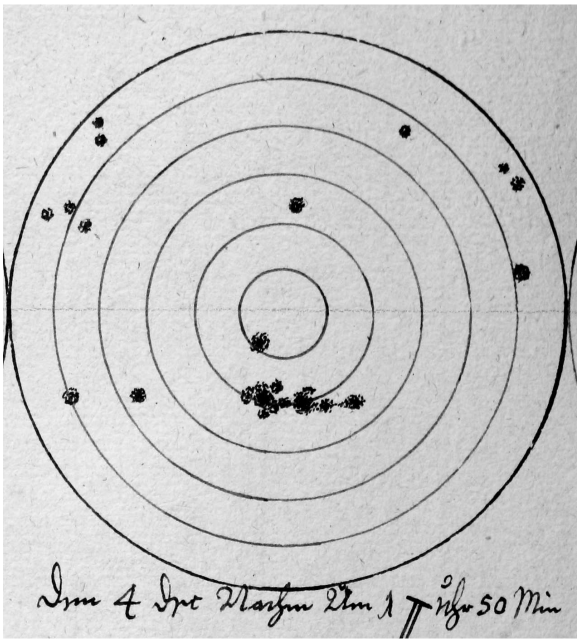

Figure 5. Drawing of 1768 December 4 with highly detailed sunspot groups.

Staudacher started with a different style of drawing on 1768 December 2. Large spots are often surrounded by many small dots representing either the penumbra or smaller spots. An example is given in Figure 5. As a side-note, howsoever the solar equator would be placed, there are very high-latitude spots in the drawing. The observation was made in the beginning of an activity cycle, and high-latitude spots are indeed quite likely.

The mention of a telescope with 3 feet focal length is of 1775. Perhaps Staudacher obtained an improved telescope in 1768 which showed him indications of a penumbra. It may also be that it was because he had the chance to see the sunspots with another telescope, or because he learnt about more precise drawings of sunspots, that he started indicating a structure in 1768. This is quite likely since the spots structures he drew are all very similar and indicate he was adding the structure from knowledge, not from the observation.

In most cases, one drawing was made for one observation. There are 73 drawings which contain the sunspot positions of two or more days. As the sunspot groups were annotated with the corresponding date, the superposition did not create any problems. Another small set of images contains additional verbal information that on a few more dates no sunspots were seen. This information has been also taken into account for the analysis.

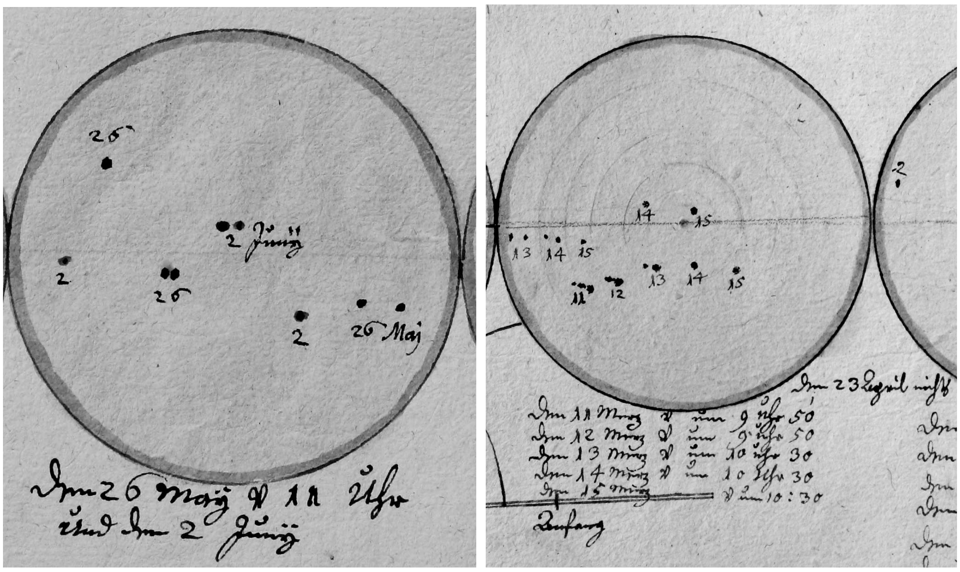

Figure 6. Left: Example of a combined drawing of two days. The dates were 1761 May 26 and June 2. Right: Example of a combined drawing of 5 days in the period of 1766 March 11–15. The image also contains valuable verbal information as *"den 23 April nichts"* (nothing on April 23).

Six observations have annotations in degrees; one of them is shown in the right panel of Figure 4. There are drawings in which a few spots do have an annotation in degrees, other spots do not. The way of writing the numbers differs from Staudacher's handwriting and may have been added later. The meaning of the numbers is unclear.

The left drawing in Figure 6 is an example of a combination of two dates in one plot: 1761 May 26 and June 2. The individual observations can be disentangled unambiguously in all the cases when Staudacher combined data. Another example with the combination of five days is shown in the right panel of Figure 6 for 1766 March 11–15, including a remark for 1766 April 23 when no sunspot was seen. We will come back to that drawing in Section 4.

Quite a few drawings contain straight lines through the centre of the disk. Horizontal lines apparently only served the purpose of aligning the circles on the book pages. The meaning of tilted lines is not easy to identify. They do not seem to indicate the position angle of the solar equator, but they do vary with the date of observation. The left panel of Figure 7 shows the combination of the observations of two days. Two individually oriented lines clearly refer to these dates. There are eight images in the entire set of drawings in which the straight lines were annotated with "Ekl" or "Ek"

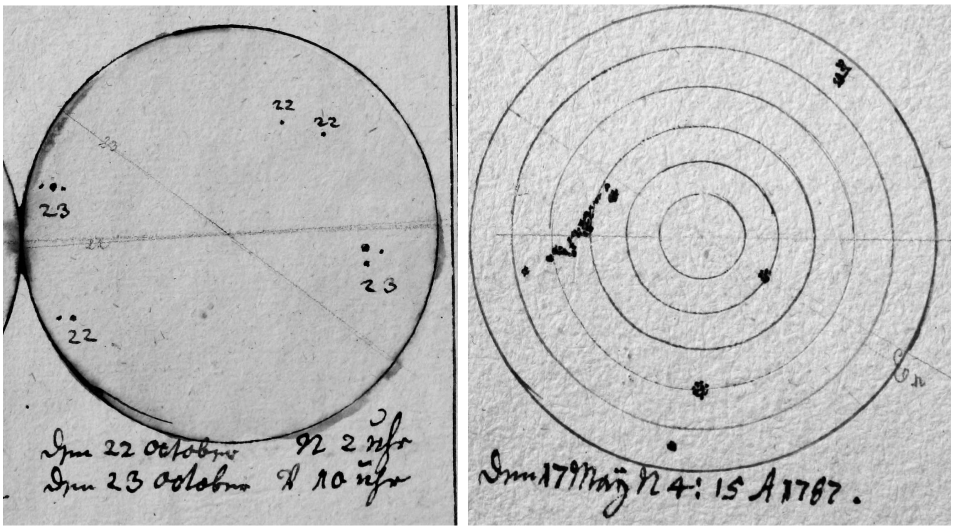

Figure 7. Combined drawing of 1767 October 22 and 23 (left). The two lines through the disk centre are marked with '22' and '23'. Drawing of 1787 May 17. The line is marked with *"Ek"* = ecliptic, but is apparently crossing the solar equator perpendicularly.

or "E" = ecliptic. It is possible that the lines in other images also show the ecliptic, but the right panel of Figure 7 indicates that this cannot be always taken for granted; the "ecliptic" crosses the probable solar equator perpendicularly. Ten images – one of them coinciding with one of the six aforementioned ones – have annotations about north, east, south, or west at the line ends. There is an image, on which south ('Süd') is marked at the top, and east ('Ost') is marked on the left edge (1762 May 4/5) and another one with east on the left and north ('N') at the bottom (1762 November 21). The latest unambiguous markings of this kind are on 1773 August 14 with north at bottom-left side and east at top-left side of the disk, and on 1774 June 16 with north at the bottom-right and east at the bottom-left of the solar disk. All these annotations indicate mirrored drawings, but we cannot conclude whether *all* the drawing had this orientation, or whether these few markings denote exceptions. The markings support the assumption that Staudacher projected the solar image with a Keplerian refractor, rather than with a Gregorian reflector which has an upright image.

An interesting case is the drawing shown between 1762 February 13 and March 2 as reproduced in Figure 8; no specific date is given. There is a single spot on the solar disk with the additional remark that "this spot was not seen on other occasions, already not on the following day, was not reddish or bluish like the other sunspots, but totally black and round, could it have been a new planet?" This is a very precise description of the difference between

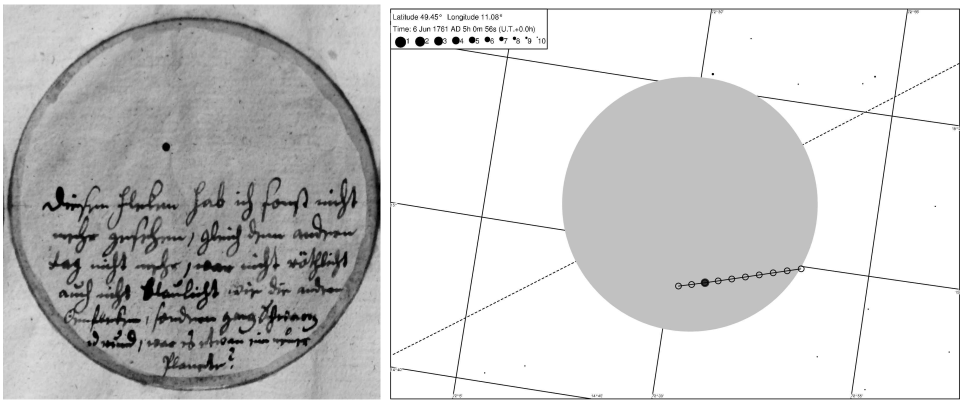

Figure 8. Left: This note was drawn between the drawings of 1762 February 13 and March 2. The text states: *"Diesen Flecken habe ich sonst nicht mehr gesehen, gleich den anderen Tag nicht mehr, war nicht rötlicht auch nicht blaulicht wie die anderen ⊙enflecken, sondern ganz schwarz und rund, war es etwan ein neuer Planeto?"* Right: Venus transit of 1761 June 6. The Venus path has ticks every hour and starts at 4 h UT, moving from left to right. Sunrise was at 3:10 h UT.

sunspots and transits seen through a very small (or poor) telescope. There was a Venus transit on 1761 June 6 visible in the German morning hours. The next transit was on 1769 June 3 visible in the evening hours. Staudacher did observe on 1769 June 3 though, but before the actual transit starting after 19h UT. Staudacher reported on the partial solar eclipse on the following day in detail. There were no Mercury transits between 1756 and 1769, the latter being on 1769 November 9 which was invisible from Germany. Since the drawing has no date, it may still refer to the transit in 1761 although it was among the 1762 images. The spot in the upper half of the Sun matches the up-side-down impression of the 1761 transit roughly, which must have been observed in the very morning near 5 h UT. There is a misplacement of several arc minutes though. If the drawing of Figure 8 was indeed the Venus transit of 1761, it sheds a bad light on the positional accuracy of the sunspots Staudacher drew.

4. Possible methods for the determination of the orientation

The following options to determine the orientation of the solar images are available, in descending order of their reliability:

- solar-eclipse drawing at the time of observation;
- consecutive observations marking the solar rotation;

– lines marked with 'N', 'Ost' (east), 'West', or 'Süd' (south) or combinations of them;

– lines marked as 'Ekl', 'Ek', or 'E' added by pencil, very likely representing the ecliptic;

– lines not labelled, either representing the celestial equator or the ecliptic;

– enough spots are visible for a guess of the orientation of the sunspot bands.

Solar-eclipse drawings are precise, but do not help, because only the eclipse of 1791 April 3 shows the path of the moon *and* the sunspots in the same image. The eclipse drawings remain interesting for the evaluation of the observing method. The Moon moves from the left to the right in the drawing of 1753 (Figure 9). The motion indicates clearly that Staudacher was plotting the mirrored image of the Sun projected by the eyepiece. The same orientation holds for the 1769 eclipse (Figure 10) when the image was plotted upside-down as it appears behind a Keplerian refractor. The 1791 drawing (Figure 11) has probably the same orientation, but the Moon path is not labelled; instead, we see the only occasion with sunspots and an eclipse in one drawing.

Also the solar rotation can be used to determine the orientation of the solar equator. The right panel of Figure 6 illustrates the displacements of spots over 4 days. The spots were apparently all near the equator; the observation was made on 1766 March 11–15, near the solar minimum, and Staudacher observed a few of the last spots of the previous cycle. A rough guess for the number of observations which can be fixed in orientation by rotation is 150–200, especially in the years 1749, 1752, 1760–1764, 1767, and 1769–1770.

Other orientation indicators are lines, sometimes marked as being the ecliptic (8 drawings), sometimes marked with one or two compass directions (10 drawings). There is a total of 188 days for which a line is given, in addition to the horizontal line often drawn to align the images on the pages of the book. While the lines would be a favourable orientation indicator, they can only be drawn with additional geometrical construction. The lines do not also consistently align with the celestial equator, i.e. the motion of the solar image on the projection screen, although the alignment is compatible with the celestial equator in a large fraction of drawings. Because 90% of the lines are not labelled, other orientation indicators should be preferred. Whenever the rotation direction can be inferred from the observations of adjacent days, that should be the preferred way of finding the orientation.

Finally, the mere distribution and shape of sunspot groups can give a hint on the position angle of the solar equator. A good example is the drawing

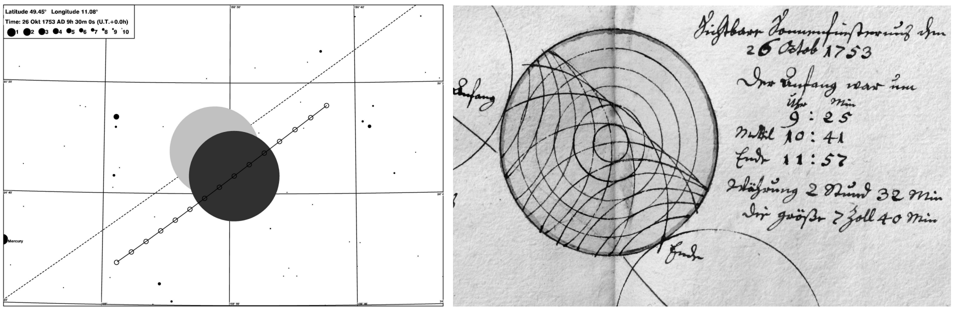

Figure 9. Geometry of the solar eclipse on 1753 October 26. The left graph shows horizontal coordinates with the upper boundary pointing to the zenith, the left to the east. The Moon path has marks at 15 minutes distance, starting at 8 h UT on the right. The observation shows the beginning at the left edge, the end of the eclipse at the right edge of the Sun.

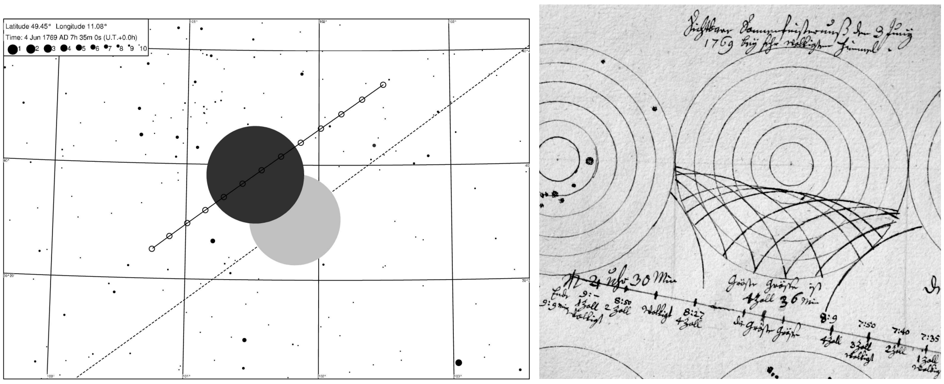

Figure 10. Geometry of the solar eclipse on 1769 June 4(3). The upper boundary of the left graph points towards the zenith, the left boundary to the east. The marks on the Moon path are at 15 min distance and start at 6 h UT on the right.

in the right panel if Figure 7 where the shape of the groups indicates that the ecliptic was most likely drawn incorrectly.

5. Estimation of sunspot areas

An automatic determination of the sunspot area was not possible, because the drawings contain quite a few dirt points, and the paper itself has often dark spots. The leftmost and the rightmost spots in left panel of Figure 4 are not sunspots, for example. We used the image manipulating programme GIMP for the determination of the sunspot area. The software has a function to show the number of pixels selected in an arbitrary region. The spots were

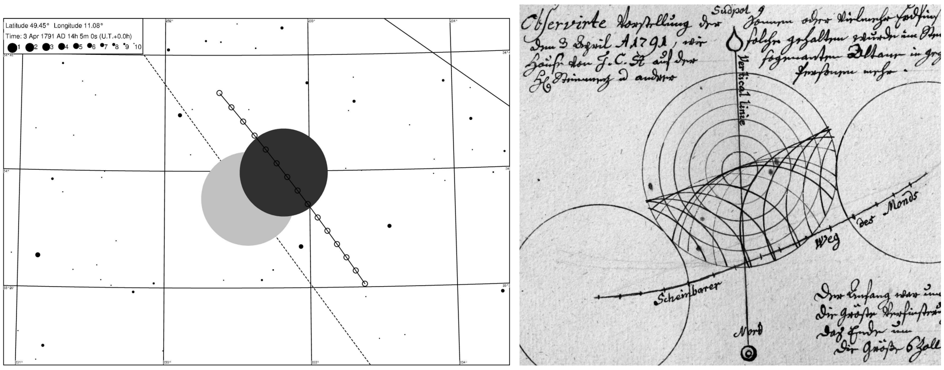

Figure 11. Geometry of the solar eclipse on 1791 April 3. The upper boundary of the left graph points towards the zenith, the left boundary to the east. The marks on the Moon path are at 15 min distance and start at 12 h UT in the lower right corner.

selected manually and their total area measured. The size of the solar disk was approximated by an elliptic selection, since the drawings are very often not perfect circles. The sunspot area A_i of a certain date t_i is then defined as the total number of sunspot pixels divided by the number of pixels in the elliptic selection.

The accuracy of the spot area measurement and the consistency of the sunspot drawings over time is very difficult to assess. Accidentally, Staudacher made two drawings in two different styles (perhaps different inks or pens) for the same date. The two drawings of 1778 January 28 were analyzed by the same procedure which was applied to all other images. The area derived from the more detailed drawing is about 30% lower than that from the bolder drawing.

Because of the relatively large number of individual drawings, averages of large numbers of observations are the only chance for meaningful results on the solar activity of 1749–1796. We made an attempt of a first analysis of the time series. Temporal averages of sunspot area are obtained by integration of the data points over time according to the trapezium rule. The whole time series is divided into averaging windows of constant length. Discrete parts of the integration are computed by $(A_{n+1} + A_n)(t_{n+1} - t_n)/2$, where A_i is the area measurement of a certain day and t_i is the date (assuming days starting at 0 h local time for simplicity). Intervals straddling the boundary of an averaging window are added, but multiplied with the fraction with which they cover the window.

Figure 12 shows the average sunspot area for the entire observing period, once with an averaging window of 183 days (half a year), and the other with a full year. The distribution of drawings over time is very uneven, and the upper panel has nine averaging windows with no data. The yearly averages

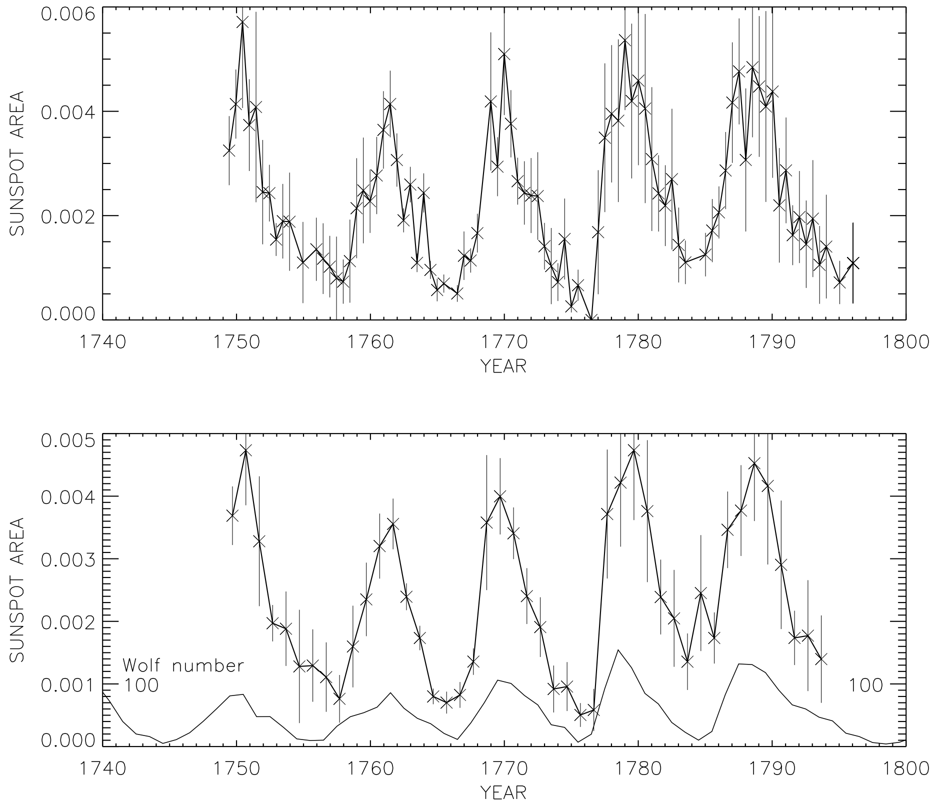

Figure 12. Average sunspot area in 183-day averages (top) and 365-day averages (bottom). The vertical lines are an indication for the error margin in that they are taken from the square root of the number of individual data points entering the average. The lower panel also contains the Wolf numbers from the SIDC, Belgium.

have no gaps though. The error margins refer to the average sunspot area divided by $\sqrt{n}$ where n is the number of observations contained by the average.

The lower panel also shows the annual Wolf numbers taken from the Solar Influences Data Analysis Center (SIDC). The agreement with the sunspot areas is fairly good. Deviations are all within the errors bar estimates added to the Staudacher sunspot areas. Possibly significant deviations may be the higher cycle maximum near 1750 and the later minimum near 1757, as compared with the Wolf numbers.

6. Discussion

The solar-disk drawings by Staudacher provide additional information about the solar cycle in the second half of the 18th century, beyond the usual Wolf numbers and group sunspot numbers. The present paper is a documentation of the digitization of the material. Positional data of the sunspots are desired, but their determination is coupled with difficulties when it comes to defining the solar equator. Scrutinization of the drawings may clarify the meaning of the straight lines. Another way of defining the solar equator is the combination of plots of consecutive days which show the displacements of the spots due to solar rotation. This is nicely demonstrated in the right panel of Figure 6. Positional data may thus be obtained for a fraction of observations.

An interesting feature of the solar cycle at the end of the 18th century is the long decline of activity after cycle 4 from about 1790 to 1797. Usoskin, Mursula, and Kovaltsov (2001) suggested a very weak cycle between the 4th and 5th cycles instead of the very long minimum between the two. Their idea is based on the groups sunspot numbers showing an additional minimum at 1793.1 and additional peak near 1795. The suggesstion is backed up by an increased number of aurorae observed in 1795 and 1796 (Usoskin, Mursula, and Kovaltsov 2002). When looking at Figure 12 we actually find a minimum for 1795 rather than a maximum. The sunspot areas do not seem to support the idea of a “lost” cycle. However, the uncertainties due to the small number of observations near the end of the 18th century could hide the true variability of the activity.

The Gnevyshev-Ohl rule suggests that odd cycles exhibit solar activity exceeding that of the preceding even cycle (Gnevyshev and Ohl 1948). Ignoring the possible “lost” cycle for the moment, we find that the sunspot areas of cycle 3 (near 1780) are higher than that of cycle 2, but we do not find agreement with the rule for the two earlier cycles 0 and 1. The sunspot areas derived from the Staudacher drawings thus do not support the even-odd rule. The change of drawing style falls in between cycles 1 and 2. A possible re-scaling or offset arising from that change are therefore not relevant for the conclusion.

Another property of the solar cycle may be the asynchronity of the cycles on the northern and southern hemispheres of the Sun (Zolotova and Ponyavin 2006). We will continue to analyse the drawings in terms of sunspot positions which will provide new information on the butterfly diagram in the 18th century, that is shortly after the Maunder minimum, and possibly about the asynchronity of the hemispheric cycles.

The author is seeking a suitable way of making the digitized images publicly available in electronic form, once the sunspot positions will have been measured.

Acknowledgements

The author is very grateful to Jan Meyer for the photographic reproductions of the drawings and to Regina von Berlepsch for the support in the library of the Astrophysikalisches Institut Potsdam. Eclipse and transit graphs were generated with the StarCalc 5.72 software by Alexander E. Zavilishin (`http://www.relex.ru/~zalex/`).

References

Hoyt, D.V., Schatten, K.: 1998, *Solar Phys.* **179**, 189.

Gnevyshev, M.N., Ohl, A.I.: 1948, *Astron. Zh.* **25(1)**, 18.

King, H.C.: 1955, The history of the telescope. Sky Publ. Corp., Cambridge, Mass.

Schroeter, I.H.: 1789, Beobachtungen über die Sonnenfackeln und Sonnenflecken samt beylæufigen Bemerkungen ueber die scheinbare Flæche, Rotation und das Licht der Sonne. Georg Adam Keyser, Erfurt.

Usoskin, I.G., Mursula, K., Kovaltsov, G.A.: 2001, *Astron. Astrophys.* **370**, L31.

Usoskin, I.G., Mursula, K., Kovaltsov, G.A.: 2002, in: H. Sawaya-Lacoste (ed.), Proc. Second Solar Cycle and Space Weather Euroconference, *ESA SP-477*, 257.

Waldmeier, M.: 1938, *Zeitschr. f. Astrophys.* **16**, 276.

Waldmeier, M.: 1960, The sunspot activity in the years 1610–1960. Zürich Schulthesss and Company AG, Zürich.

Wilson, A.: 1774, *Philosophical Transactions* (1683-1775) **64(I)**, 1

Zolotova, N. V., Ponyavin, D. I.: 2006, *Astron. Astrophys.* **449**, L1.