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Sunspot Positions and Areas from Observations by Pierre Gassendi

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Abstract Solar activity behaviour on the eve of the Maunder minimum may provide important information on the period of further suppression of sunspot population. We analyse sunspot positions and areas in the 1630s extracted from rare drawings published by Pierre Gassendi in *Opera Omnia*. This work was published in two different editions, the first in Lyon and the second almost 70 years later in Florence. The drawings published in Lyon are found to be slightly different from those published in Florence, which produces a discrepancy in the position of spots of a few degrees, while sunspot group areas may differ by a factor of two. We reveal that the orientation of the drawings in the book is not always the same as might be seen in the telescope. We conjecture that the time of Gassendi's observations covers the beginning of a new Schwabe cycle in the southern hemisphere. The differential rotation rate in the 1630s is also assessed and discussed.

Keywords Sunspots · Solar cycle, observations · Sunspots, velocity

1. Introduction

The time–latitude distribution of sunspots, the so-called butterfly diagram, was substantially reconstructed back to 1825 (Pelt *et al.*, 2000; Arlt, 2008, 2009; Leussu *et al.*, 2016). Earlier sunspot records are also digitised and analysed (Vaquero, 2007; Carrasco, Álvarez, and Vaquero, 2015; Neuhäuser *et al.*, 2015; Arlt *et al.*, 2016; Carrasco and Vaquero, 2016; Senthamizh Pavai *et al.*, 2016; Carrasco *et al.*, 2018; Vokhmyanin and Zolotova, 2018). To improve our understanding of the long-term scaling of solar activity (Clette *et al.*, 2016), the

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revised and recalibrated group numbers were recently announced (Clette *et al.*, 2014, 2015; Svalgaard and Schatten, 2016; Vaquero *et al.*, 2016). In addition to sunspots, there are reconstructions of a hundred-year series of solar faculae (Nagovitsyn, 1988; Muñoz-Jaramillo *et al.*, 2012), filaments (Tlatova, Vasil'eva, and Tlatov, 2017), heliospheric magnetic field (Svalgaard and Cliver, 2010; Owens *et al.*, 2016), and others.

The solar activity behaviour on the eve of the grand minima (Eddy, Gilman, and Trotter, 1977; Casas, Vaquero, and Vazquez, 2006) may shed light on fundamental properties of the solar dynamo (Sokoloff and Nesme-Ribes, 1994; Küker, Arlt, and Rüdiger, 1999; Brandenburg and Spiegel, 2008; Karak and Choudhuri, 2012; Passos *et al.*, 2014; Kitchatinov, Mordvinov, and Nepomnyashchikh, 2018).

In this paper, we process sunspot drawings from 1633 to 1638 made by the French priest and astronomer Pierre Gassendi. His six-volume work is known as *Opera Omnia*. Rare sunspot observations were published in the fourth volume, *Astronomica*, together with astrometric measurements of the Sun, the Moon, Mars, Venus, Jupiter, Saturn, *etc.* In 1658, the book was published in Lyon (Lugduni) by Anisson and Devenet, and in 1727, a second version was republished in Florence (Florentiæ) by Celsitudinis. The engraving of drawings in these editions differ, which is noticeable for large sunspots. The orientation of the images does not always coincide, which at a glance indicates that the orientation of the drawings in the book is not always the same as might be seen in the telescope. *Opera Omnia* also contains drawings of the eclipse, and these are also different in the two editions.

Section 2 of this work is devoted to evaluating the sunspot-group areas and to counting them. In Section 3 we address the sunspot heliocoordinates. The butterfly diagram and differential rotation are analysed in Section 4. A summary is given in Section 5. An Electronic Supplementary Material file provides the results.

2. Areas and Number of Groups

The sunspot observations were made by means of a Galilean telescope ("Telescopio") in a room with closed windows and doors ("ianua, fenestrisque aliunde occlusis"). The image of the Sun was projected onto a sheet of paper (van Helden, 1976). The depicted circle probably had a diameter of 10 inches or about 25 cm ("decussis pedis Parisiensis", which could be translated as ten small units of the Paris foot; from private correspondence with Roger Ceragioli). The diameter was divided into 120 equal parts (or subunits). For several sunspots, Gassendi gave their width and distance to the limb, disc centre, and ecliptic ("Eclipticae") or diameter ("Diametri") in subunits. Note that the transit of Mercury on 7 November 1631 observed in Paris was projected onto a circle with a diameter of three-quarters of a Paris foot ("dodranti pedis Parisiensis"), that is, 9 inches or about 23 cm, divided into 60 subunits. In our work, we rescale each image of the solar disc to a diameter of 1400 pxl.

We sorted 57 spots into 17 groups. In Figure 1a, our group counts slightly differ from those of Hoyt and Schatten (1998). Vaquero *et al.* (2011) eliminated one spurious observation by Gassendi on 1 December 1638 from the group sunspot numbers [R_g]. This record does not appear in *Astronomica*. Another data point that also should be removed is the observation on 7 November 1631, when the transit of Mercury had been reported. Gassendi thought that it was a spot that he had not noticed on the Sun on the previous day. Later he realised that he was indeed observing the planet (van Helden, 1976, for more details).

Like Vokhmyanin and Zolotova (2018), we calculate the area of sunspots in microhemispheres [msh]. Figure 1b shows the areas of the individual sunspot groups from the book published in 1658 in Lyon; the largest is Group G17 on 1 November 1638 with 5958 msh.
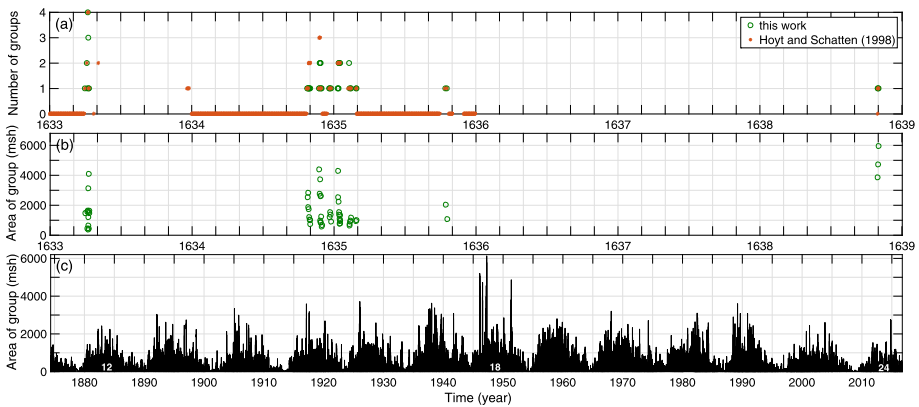
Figure 1 (**a**) *Red* denotes the number of groups according to Hoyt and Schatten (1998), and *green* shows groups of this work. The area of each sunspot group from Gassendi (1658) is shown in panel (**b**), and that of the Greenwich catalogue in panel (**c**). *White* numbers define the cycle number according to the Zürich numbering.

For the first observations, Gassendi gave a size and position of sunspots in subunits of the solar disc. We compared these values in the text with the sizes of spots in drawings of the Lyon book and found that they are in good agreement. If Gassendi indeed observed powerful sunspot populations, it might indicate that the time of Gassendi's (1630s) as well as Galilei's (early 1610s) and Scheiner's (1611 – 1631) observations fall on a secular maximum of the solar activity. For instance, areas of individual groups exceeding 4000 msh were observed during Cycle 18 (Figure 1c, data from RGO/USAF/NOAA). Huge active regions should be accompanied by numerous small groups, which were not reported by Gassendi. The smallest group is G5 on 9 April 1633 with 388 msh. Given that groups smaller than 400 msh make up about 90% of all groups in the Greenwich catalogue, the Gassendi observations may lack a significant portion of sunspots.

On the other hand, Gassendi showed sunspots in a schematic manner; neither umbra nor penumbra were depicted. Therefore, the sunspot areas have a significant uncertainty. We would also like to point out that the sunspot size is usually exaggerated in some historical drawings (Carrasco *et al.*, 2018, *e.g.*). Moreover, there are systematic discrepancies between the photographic and sunspot drawing databases (Baranyi *et al.*, 2001).

To demonstrate the discrepancy between historical drawings and the RGO/USAF/NOAA database, we compared their distributions. Figure 2 shows the distributions of sunspot group area for Gassendi with blue bars, for Galilei from Vokhmyanin and Zolotova (2018) in magenta, and modern observations in red, green, and blue. The majority of the Gassendi drawings covers almost half a year from October 1634 to February 1635. From the modern observations, we chose three half-year periods with the largest medians of the sunspot group area distribution (June – November 1874, May – October 1889, and May – October 1957). The distribution for Galilei's drawings is consistent with modern data, while the median of Gassendi's distribution is shifted to larger sunspot groups. Moreover, the occurrence frequency of medium and large groups exceeds that for modern data. Apparently, the size of the groups in Gassendi's drawings is enlarged.

Figure 3a compares the two large groups G11 (4286 msh) and G17 (5958 msh) from Gassendi's drawings as published in 1658 in Lyon. For comparison, we overlay active regions AR338 from the Kislovodsk Solar Station and AR14886 from the Greenwich photo-

Figure 2 Probability density functions of the sunspot group area from Gassendi's (*blue*) and Galilei's (*magenta*) drawings and three half-year periods of modern observations.
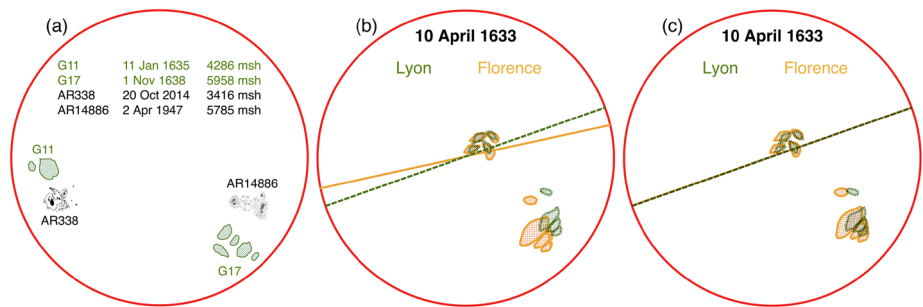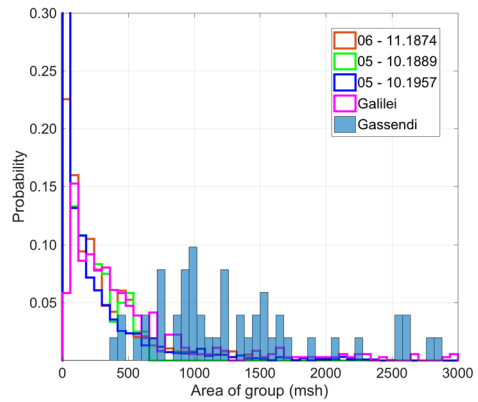
Figure 3 (**a**) Overlap of two of Gassendi's observations with those from the Kislovodsk Solar Station (Tlatov *et al.*, 2014) and the Greenwich photoheliographic catalogue (Baranyi, Győri, and Ludmány, 2016; Győri, Ludmány, and Baranyi, 2017). Date and group area are added. (**b**) Overlap of two images of the observation on 10 April 1633 from the books published in Lyon (Gassendi, 1658, *green*) and Florence (Gassendi, 1727, *orange*). (**c**) The drawing from the Florence book is rotated to fit the drawing from Lyon.

heliographic catalogue (*i.e.* the largest active region of NOAA AR14886). The position of Group AR14886 is shown reversed from right to left limb.

We found that the drawings of *Opera Omnia* published in Lyon in 1658 differ from those published in Florence in 1727. The Electronic Supplementary Material file provides sunspot positions and areas extracted from Gassendi (1658). Figure 3b compares the images for 10 April 1633 from the two books. The different inclination of the diameters indicates that the orientation of the solar disc in *Opera Omnia* might not be the same as was seen in the telescope. The sunspot latitudes in the Lyon and Florence images diverge by up to 3° (Figure 3c). A group composed of three spots that are bound together has an area of about 4100 msh in the Lyon book and about 8000 msh in the Florence book. This shows that sunspot-group areas may differ by a factor of two.

Ironically, the problem of uniformity of a sunspot-group area as measured at various observatories has not been solved so far. For instance, according to the Kislovodsk Solar Station, AR338 has an area of 3416 msh (on 20 October 2014) and 4096 msh (on the next day); according to RGO/USAF/NOAA, this active region is defined as AR12192 with 2180 msh (on 20 October) and 2410 msh (on the next day), *i.e.* the discrepancy is of the order of tens of percent.

3. Sunspot Positions

We recall that we define the sunspot positions based on the Lyon book. The series of sunspot observations on 1–12 April 1633 was made in Diniæ or Diniâ (today Digne-les-Bains, 44°05′N and 6°14′E), from 25 October 1634 to 28 February 1635 in Aquas-Sextias or Aquis-Sextijs (today Aix-en-Provence, 43°32′N and 5°27′E), and since 15 October 1635 again in Diniæ.

The style of the drawings is not uniform. In the first series of observations from 1–12 April 1633, Gassendi usually drew a new solar image for each subsequent day. Since 25 October 1634, he presented trajectories of sunspots across the disc over several days.

On 1–12 April 1633, the position of the solar diameter was fixed at around 9 o'clock in the morning. However, the scatter of sunspots on the disc indicates that either they were drawn at different times during the day and/or the images were rotated. On 13 April 1633, Gassendi observed the Sun at 7, 8, 9, and 10 o'clock and claimed that there were no more traces of sunspots ("sed nullum amplius Maculæ vestigium"). We recall that Gassendi reported large spots, hence this statement does not necessarily indicate vanishing sunspot activity at the end of a series of observations.

On 25 October 1634, within the first noon hour ("sub horam quidem primam à meridie"), Gassendi discovered a double ("gemellam") sunspot, the first for a long time, as he stated. At about the same hour on the next day, Gassendi saw this double sunspot accompanied by a smaller spot ahead and two spots behind. At noon of 27 October, the same objects were vaguely visible. At noon of 28 October, the double sunspot was visible, but the front and two trailing spots had disappeared. Subsequent observations were also made at noon.

Around or after noon ("sub meridiem") on 24 November 1634, the sunspot observation was made by secretary Antonius Agarratus, who also assisted Gassendi in his astrometric measurements. He saw a double spot ("Maculam geminam detexit") that lived up to the first day of December. Several smaller sunspots are depicted between two large ones in the drawings of this group. Subsequent observations were not always made precisely at noon ("quòd non fuerit semper exquisitè meridies"). After the sunspot group went beyond the limb, Gassendi wrote that on days 2, 3, 5, 6, 7, 8, 9, 10, 11, 12, 14, and 15 December there were no sunspots.

On 20 December 1634 and on subsequent days of this series, the observations were made in the afternoon.

From 11 to 17 January 1635, Gassendi did not indicate the time of sunspot observations.

From 7 to 10 February 1635, Gassendi presented astrometric and weather reports. He briefly noted that on 10 February and on the following days, sunspots were observed.

On 27 and 28 February 1635, the time of the sunspot observations is unknown.

On 15 October 1635, a triple sunspot appeared. The sunspot was also observed on 19 October. Gassendi reported spotless days from 24 October to 27 October and from 29 October to 2 November.

On 30 October 1638, after the altitude of the Sun reached 26°, Gassendi wrote that near the vertical of the solar image, to the east and down, sunspots appeared. On the next day, these sunspots were observed in the morning and in the evening. On 1 November, the observation time is unknown.

This was a partial translation of Gassendi's reports on sunspots. The time of the observations is not clearly stated or mentioned. We assume that on 8–12 April 1633, Gassendi did not observe the sunspots at 9 o'clock; the images could also have been rotated prior to publication (Figure 3b). These findings cause us to ignore the time stamps and instead seek for the right angle of the image at which the spot latitudes would be constant from day to
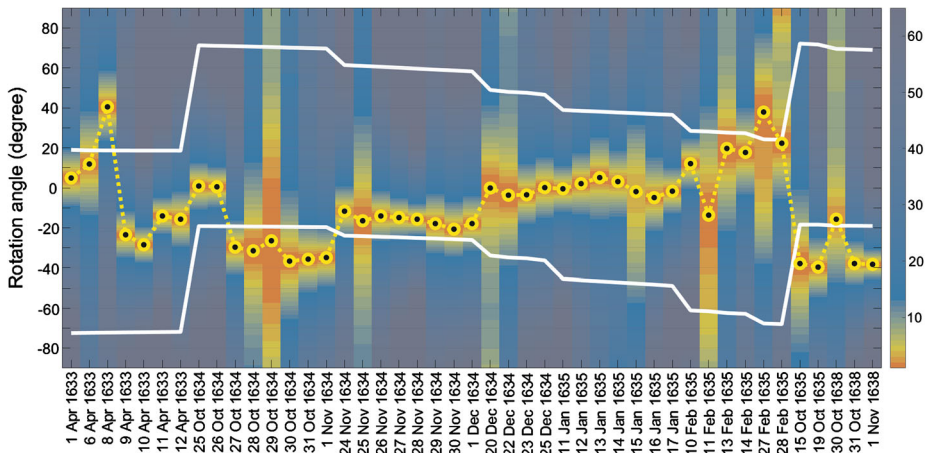
Figure 4 *Coloured bars* show the value of the discrepancy *F* between the sunspot latitudes for each day. *Black points* joined by the *dotted yellow curve* mark the minima of *F*. *White lines* mark the limits of the angle between the zenith and the Sun's rotation axis as seen from Digne-les-Bains or Aix-en-Provence.

day. Sunspots of each individual day were transferred to a separate solar disc. Then, by rotating images from $-90°$ to $90°$ (in increments of $0.2°$), we minimised the discrepancy (we define this value as *F*) between the sunspot latitudes. This technique is described in detail in Vokhmyanin and Zolotova (2018).

For each day, the coloured bars in Figure 4 show *F* whose minimum values (black points joined by the dotted yellow line) define the best fit of the sunspot positions along the latitude bands from day to day. There is no noticeable minimum of *F* (*e.g.* on 29 October 1634), because the only sunspot group was drawn near the disc centre. White lines mark the limits of the angle between the zenith and the Sun's rotation axis at Digne-les-Bains or Aix-en-Provence. In a few days, the minima of *F* are located outside of these limits, which indicates that the orientation of the drawings in the book is not the same as was seen through the telescope.

The Electronic Supplementary Material file provides the time of observations, which is defined by the minimum of *F*. This time is valid on the assumption that the solar disc orientation is the same as was seen in the telescope.

On 8 April 1633 at Digne-les-Bains, Gassendi observed the annular solar eclipse. He presented a table containing phases of the eclipse and published three drawings. The beginning of the eclipse was not observed because of weather conditions, but the end of the eclipse was perfectly visible, according to Gassendi. He stated that the eclipse began at 15:40 local time, reached maximum at 16:42, and ended at 17:45. According to the calculations made in the CalSky project designed by Arnold Barmettler, the eclipse began at 15:16 local time, reached maximum at 16:26, and ended at 17:30.

Figure 5a shows the first drawing of the eclipse. We overplot the drawing from the Lyon book (green) with that of the Florence book (orange). The black thin line with an arrow at the top is the vertical, and the inclined line is the solar diameter as defined by Gassendi. The time of this drawing is not mentioned. The linear size of the Sun is depicted as about two-thirds of that of the Moon.

Gassendi showed two drawings when the Moon touched a somewhat red sunspot ("Tunc temporis subrufa erat in ☉ macula, quam utrum tetigerit, vel etiam obtexerit Luna"). Two
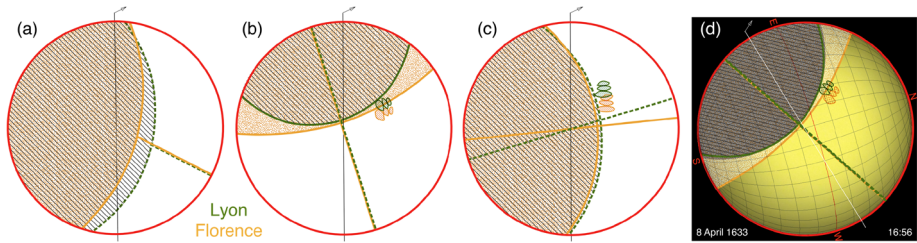
Figure 5 Observation of the annular solar eclipse on 8 April 1633. Panels (**a**), (**b**), and (**c**) show an overlap of pairs of sketches from the books published in Lyon (Gassendi, 1658, *green*) and Florence (Gassendi, 1727, *orange*). The *black thin line* is the vertical. (**d**) Overlaid derotated observation from the Lyon book, a simulated image of the eclipse by Arnold Barmettler (the CalSky Project), and the heliographic grid at 16:56 on 8 April 1633 at Digne-les-Bains.

phases are presented: the Moon covers and uncovers the sunspot ("idcircò apponere placet duo Schemata, seu duas illas Phaseis quibus macula & contecta est, & retecta").

Here, we conjecture that at first Gassendi described the phase of the uncovering of the sunspot (Figure 5b), and then he showed the sunspot before it was covered by the Moon (Figure 5c). Figure 5b reveals the different size of the Moon in the Lyon and Florence books. Figure 5c shows identical positions of the Moon, but different positions of sunspots and the solar diameter. Note that the diurnal rotation of the heliographic grid is about 2° during the whole eclipse, hence the sunspots were only very little displaced. The alignment of the solar diameters in Figure 5c results in different positions of the sunspots and different positions of the Moon. Together with the findings described in Section 2, this indicates that sunspot latitudes and longitudes are accurate to within a dozen degrees.

Gassendi indicated that one of the eclipse observations was made at 16:56. Figure 5d shows an overlay of the rotated drawing from Figure 5b, the heliographic grid, and the calculated location of the Moon (black sector) as it was seen at 16:56 in Digne-les-Bains. The size of the Moon in the Lyon sketch and in the calculated image coincides perfectly. Therefore, this sunspot group G3 was located at 13° in the northern hemisphere. On the other hand, such a large group (1641 msh) is very unlikely to live for only one day. Our method, which minimises the discrepancy between the sunspot latitudes, evaluated that this sunspot group successfully complements the trajectory of the triple-sunspot group G2 in the southern hemisphere from 6 to 12 April 1633.

Figures 6 and 7 show that the sunspots pass over the solar disc, constructed in accordance with the F minima. The heliographic grids correspond to the middle of a series of observations. The dashed thin curves schematically mark trajectories of several sunspots. On 8 April 1633, two possible positions of the same sunspot group are shown: version 1 is defined from the solar eclipse, and version 2 from the minimum of F. The Electronic Supplementary Material file provides the two possible sunspot positions on 8 April 1633. Version 1 or 2 may be chosen. Here, we also presume that the presence of sunspots on the equator on October and November 1634 results from the uncertainty of the sunspot positions.

4. Butterfly Diagram and Differential Rotation

Figure 8 shows the butterfly diagram for 1610 – 1650. Blue circles denote observations made by Galilei (Vokhmyanin and Zolotova, 2018), red squares show Scheiner's observations (Arlt *et al.*, 2016), green stars represent Gassendi's observations that we processed here,
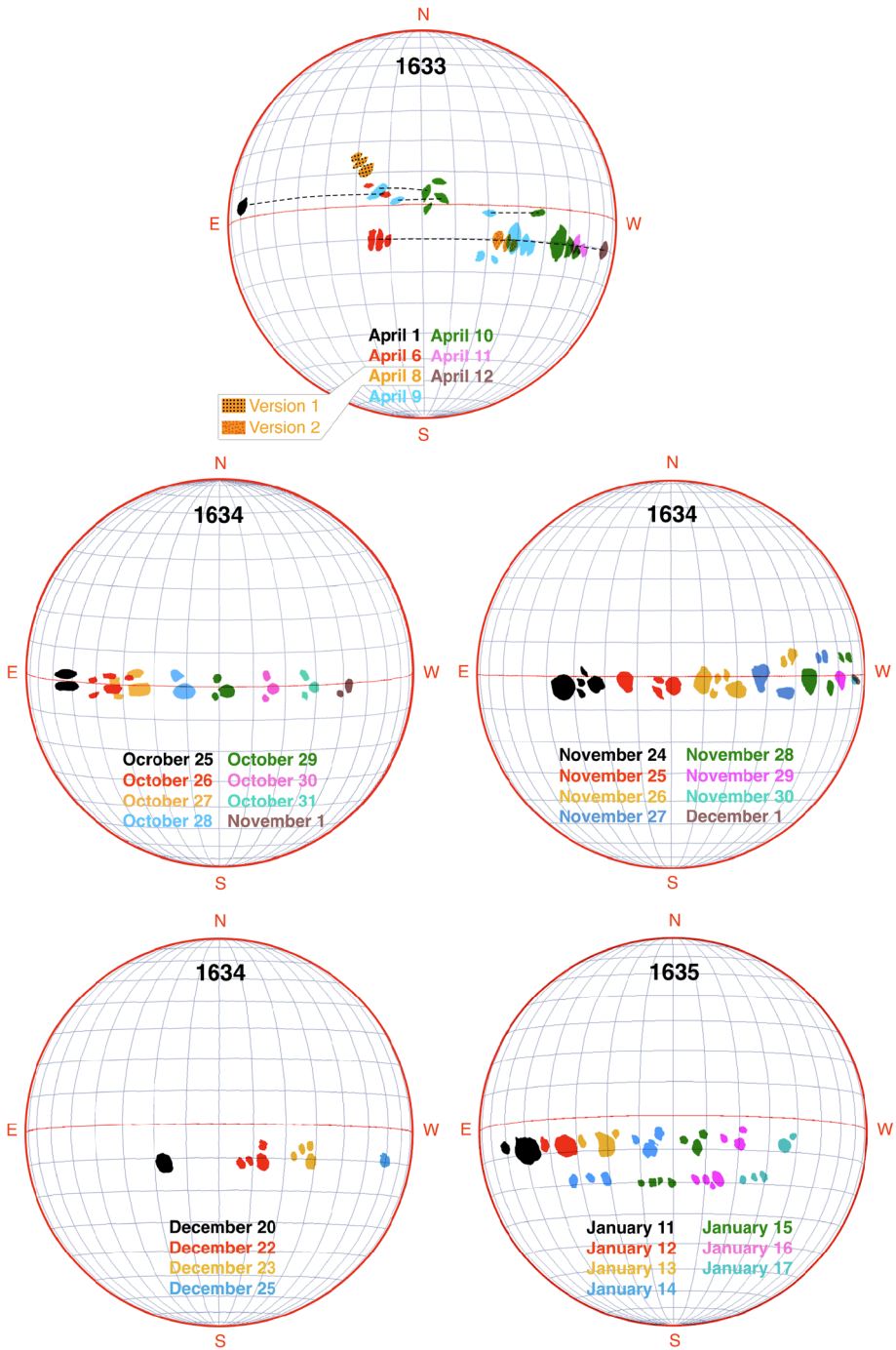
Figure 6 Combined schematic coloured sketches of Gassendi's observations. Solar images of individual days were derotated to minimise the function F. The heliographic grids correspond to the middle day within the observation series. On 8 April 1633, two possible positions of the sunspot group (Version 1 and 2) are shown. The *dashed thin curves* schematically mark trajectories of several sunspots.
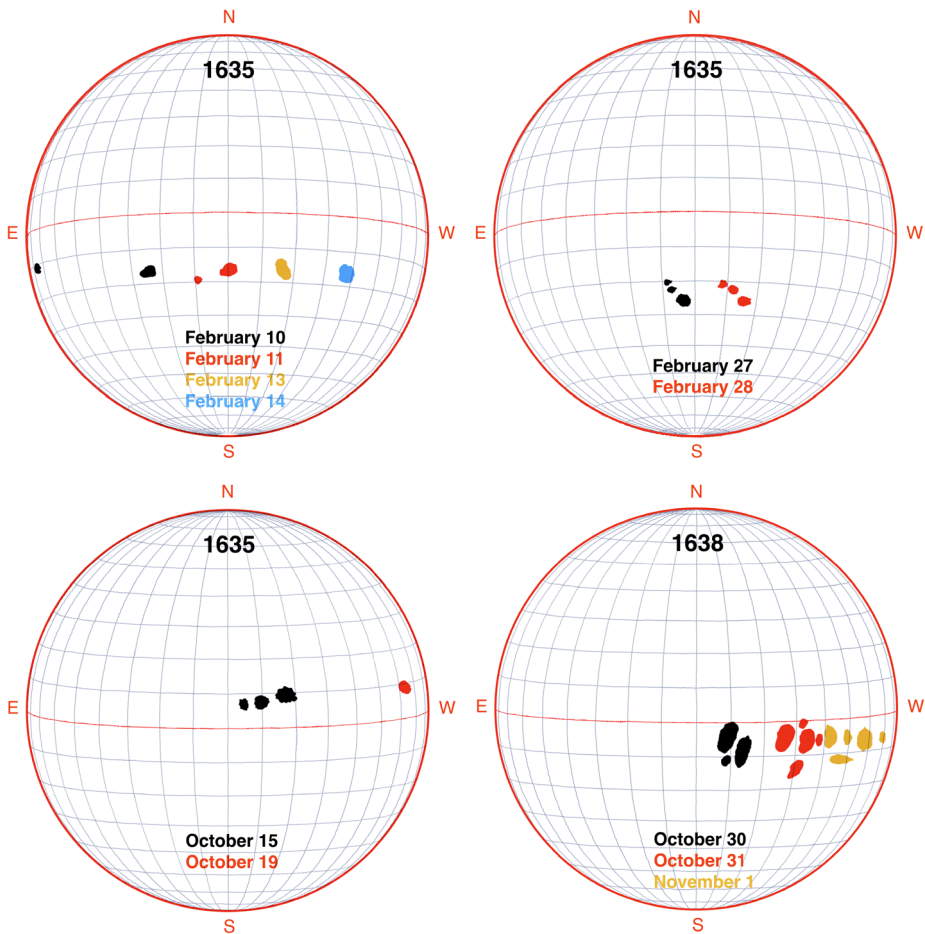
Figure 7 Combined schematic coloured sketches of Gassendi's observations. Solar images of individual days were derotated to minimise the function F. The heliographic grids correspond to the middle day within the observation series.

and grey dots show the reconstruction by Elizabeth Nesme-Ribes from Soon and Yaskell (2003). According to Nesme-Ribes, Gassendi reported sunspots around the beginning of 1634. However, we did not find these observations.

Blue and red bars correspond to the proposed solar minima and maxima (Gleissberg, 1944, 1967; Gleissberg, Damboldt, and Schove, 1979; Schove, 1955, 1979; Wittmann, 1978; Vitinskij, Kopetskij, and Kuklin, 1986; Lassen and Friis-Christensen, 1995). Yellow ovals depict the apparent of the butterfly wings. We would like to suggest that 1633 – 1635 exhibits an overlap of two sunspot cycles. A new Schwabe cycle started probably in the southern hemisphere. This hemisphere allegedly was in the lead in the early 1620s (Neuhäuser and Neuhäuser, 2016).

Figure 9 compares the differential rotation rates from the Greenwich catalogue and according to our evaluation from Gassendi's drawings. The differential rotation is described by the following equation: $\omega(B) = a + b \sin^2 B$, where B stands for heliographic latitude. The dashed green curve represents the expression $\omega(B) = (14.55 \pm 0.006) - (2.87 \pm 0.06) \sin^2 B$
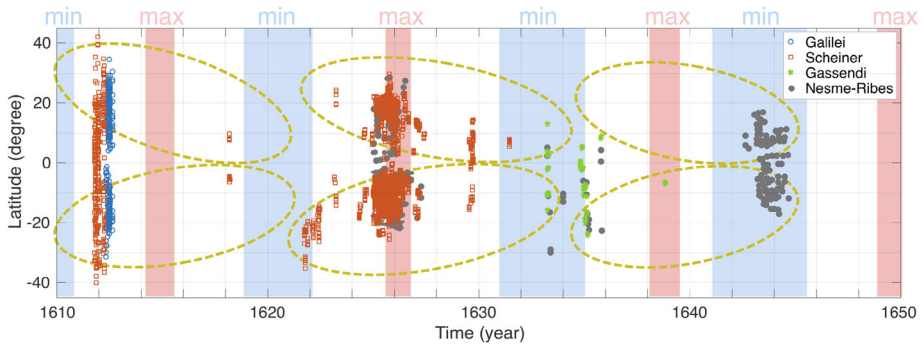
Figure 8 Butterfly diagram. *Blue circles* denote observations by Galilei (Vokhmyanin and Zolotova, 2018), *red squares* show Scheiner's observations (Arlt *et al.*, 2016), *green stars* represent Gassendi's observations that we processed here, and *grey dots* show the reconstruction by Nesme-Ribes (Soon and Yaskell, 2003). *Blue* and *red bars* correspond to the proposed solar minima and maxima. *Ovals* depict the apparent butterfly wings.
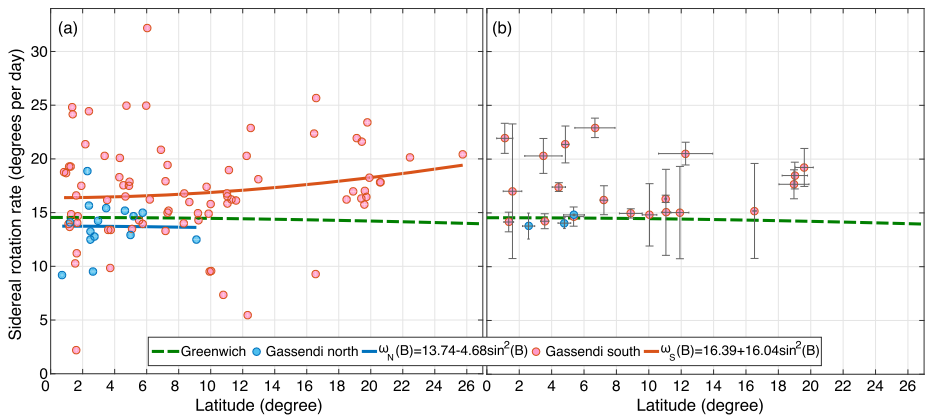
Figure 9 Comparison of the differential rotation rates from the Greenwich catalogue defined by Balthasar, Vázquez, and Wöhl (1986, *dotted-green curve*) and observations by Gassendi (1658) for the north (*blue*) and south (*red*). *Thick solid curves* denote the fitting functions. (**a**) *Each circle* denotes the sidereal rotation rate of a sunspot from day to day; (**b**) the average sidereal rotation of sunspots calculated over a series of observational days.

defined by Balthasar, Vázquez, and Wöhl (1986) using the Greenwich data. For Gassendi's observations, the sidereal rotation rate of sunspots in the northern hemisphere is shown in blue and in the southern hemisphere, it is shown in red.

The day-to-day variance of sunspot longitudes is presented in Figure 9a. The corresponding fitting functions $\omega_N(B) = (13.74 \pm 1.81) - (4.68 \pm 219.72)\sin^2 B$ (north) and $\omega_S(B) = (16.39 \pm 1.36) + (16.04 \pm 23.87)\sin^2 B$ (south), defined by means of the least-squares method, are also displayed. Note that for the southern hemisphere, b is positive, which implies the anti-solar type of differential rotations. However, because observations are rare, the drawing style is schematic, there are uncertainties on the time of observation and errors in the printing of drawings *etc.*, these fitting functions are rather a result of multiple ambiguities than a real phenomenon. For instance, the longitudinal distance between the

sunspots on 26 and 27 November 1634 in Figure 6 is less than 10°, while that of sunspots on 24, 25, and 26 November 1634 is about 20°.

Figure 9b shows the average sidereal rotation of sunspots calculated over a series of three or more observational days using a linear approximation of longitude changes. The horizontal error bars are defined as the standard deviation of the sunspot latitude. The vertical error bars are the average of the absolute deviations from the linear approximation.

5. Conclusions

We processed sunspot drawings made by Pierre Gassendi in 1630s. We calculated areas of sunspot groups and their positions based on his book *Opera Omnia*.

The areas are found to be comparable with the all-time largest sunspots of Cycle 18. This in turn may indicate that observations by Galilei, Scheiner, and Gassendi were made in a secular maximum. However, the sunspot-group areas in some drawings differ by almost a factor two in the books published in Lyon (1658) and Florence (1727). This indicates great uncertainty in the areas of the sunspots drawn by Gassendi.

Using a method that minimises the discrepancy between the sunspot latitudes from day to day, we defined the sunspot heliocoordinates. For 12 days, the apparent orientation of the solar disc exceeded the maximum angle of the diurnal clockwise rotation of the Sun from sunrise to sunset; the observation time is therefore not clear for these days.

We analysed the butterfly diagram and suggest that the period of 1633 – 1635 could be a solar minimum in which a new Schwabe cycle started in the southern hemisphere. The evaluated sidereal rotation rate in the southern hemisphere in the 1630s might exceed that of the modern era. We suggest that this could be a result of numerous uncertainties. The final result is tabulated in the Electronic Supplementary Material.

Disclosure of Potential Conflicts of Interest   The authors declare that they have no conflicts of interest.

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