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Solar Activity Level in 1611–1613: Sunspot Groups and Areas

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Abstract—Early telescopic sunspot observations provide unique information extending our knowledge on solar activity back to the seventeenth century. In our work, we analyse sunspot parameters reconstructed from observations in the 1610s. Comparing distributions of historical and modern sunspot group areas, the fraction of small sunspots apparently missing in historic drawings was estimated. We suggest that reports might lack from 20 to 85% of sunspot groups depending on the style of observations. The number of sunspot groups corrected for the fraction of lost spots indicates that the period of 1612–1613 apparently belongs to a cycle of a secular maximum.

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1. INTRODUCTION

Digitization and analysis of the historical manuscripts have been actively restarted since the 2010s (Clette et al., 2014; Svalgaard et al., 2015; Svalgaard, 2017; Carrasco et al., 2019, 2020; Arlt and Vaquero, 2020; Silverman and Hayakawa, 2021; and many others). A wide range of solar parameters is evaluated (Vaquero and Vázquez, 2009; Leussu et al., 2016; Neuhäuser et al., 2018; Pevtsov et al., 2019; Hayakawa et al., 2021). The classic measures of solar activity are the Sunspot Number (SSN) and the Group Sunspot Number (GSN by Hoyt and Schatten (1998)) or Group Number (GN by Svalgaard and Schatten (2016)). These long time-series are affected by the diversity of observational methods exploited by numerous solar astronomers. Another measure that might seem to be less arbitrary (Petrovay, 2020) is the total area of sunspot groups (A). Since the number of small sunspot groups (hereafter groups of an area <100 msh) exceeds the number of regular and large groups, one can assume that the reconstructed from early historical archives group numbers suffer from lack of small groups (Karachik et al., 2019) much more than the total area index.

In this paper, we roughly estimate the fraction of small sunspot groups which probably emerged in the Sun, but are absent in reports of the 1610s. Also, magnitudes of historical sunspot group numbers and areas are compared with those of RGO/USAF/NOAA database (hereafter RGO).

2. DATA

We analyse reconstructed solar data from observations by Thomas Harriot from 18 December 1610 to 28 January 1613 (Vokhmyanin et al., 2020) whose digital copy is stored in ECHO—Cultural Heritage Online; observations by Galileo Galilei on 3–11 May 1612 reported in his letters to Cardinal Maffeo Barberini (Manuscript Barb.lat.6479 of the Biblioteca Apostolica Vaticana), on 2 June–8 July, and 19–21 August 1612 published by Galilei (1613), processed by Vokhmyanin and Zolotova (2018a); series of observations by Galilei on 12 February–3 May 1612, Lodovico Cardi known as Cigoli on 18 February–23 March 1612, 29 April–6 May 1612, and 18–25 August 1612, Sigismondo di Cologna on 6 September–9 October 1612, Christopher Scheiner on 1 August 1613, Fabio Colonna on 1 August–30 September 1613 and 3 October 1614 stored in the Galilean collection of the Central National Library of Florence and processed by Vokhmyanin et al. (2021); observations by Pierre Gassendi (1658) processed by Vokhmyanin and Zolotova (2018b).

3. RESULTS

Figure 1 shows the fractional distribution of sunspot group areas defined from historical and modern observations. The common feature of the considered historical sunspot reports is the reduced number of small sunspot groups ($A < 100$ msh), up to their absence in drawings by Cologna and Gassendi. Therefore, medians of these distributions exceed 200 and even 1000 (Table 1) for Gassendi who apparently drew exaggerated sunspot groups. The latter fact does not allow us to estimate the solar activity level in the 1630s. The largest portion of small groups was reported by Colonna (Colonna plus one observation by Scheiner)—17.3%, whose cumulative area composes 4.2% of the

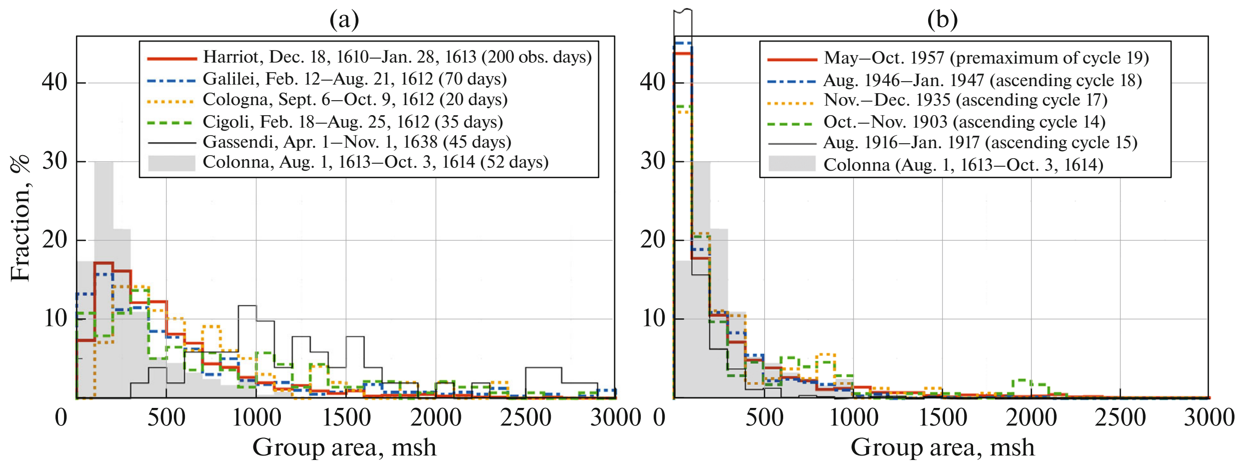

Fig. 1. Fractional distribution of sunspot group areas of different observers and of RGO database.

cumulative area of all spots drawn by Colonna (Table 1). Also, this observer reported almost twice as many groups with an area from 101 to 200 msh in comparison with others.

In order to compare observations of the 1610s with modern observations (RGO since 1900), we should choose nearly the same duration of observations, for example, 2 and 6 months. Note that area distribution of time intervals of one month or one year are similar to the chosen ones.

According to Gleissberg (1944, 1967), Gleissberg et al. (1979), Schove (1955, 1979), Wittmann (1978), Vitinskij et al. (1986), and Lassen and Friis-Christensen (1995), solar minimum occurred in 1608.0–1610.8 and solar maximum in 1613.3–1615.8. Sunspot observations of 1610–1613 should belong to the ascending phase or maximum of a cycle. Distributions of sunspot group areas of RGO satisfying these conditions contain a fraction of small sunspot groups varying from ~35% to almost 70% (subsets of daily data from one month to a year in length with monthly stepsize were analyzed). Medians of these distributions vary from ~30 to 170 (Table 1). Obviously, the larger is the median, the smaller is the fraction of small sunspot

Table 1. Fraction (%) of sunspot group counts with areas <100 msh and fraction of their cumulative area in historical observations and at selected time periods of RGO/USAF/NOAA database. Column Median shows the median values of the sunspot group areas distribution

Time period	Median	Fraction of groups of A < 100 msh, %	Fraction of cum. area of A < 100 msh, %
Harriot, Dec. 1610–Jan. 1613	377	7.2	1
Galilei, Feb.–Aug. 1612	400	12.7	1.1
Cologna, Sep.–Oct. 1612	536	0	0
Cigoli, Feb.–Aug. 1612	579	10.3	0.7
Gassendi, Apr. 1633–Nov. 1638	1234	0	0
Colonna, Aug. 1613–Oct. 1614	205	17.3	4.2
Premaximum cycle 19, May–Oct. 1957	132.5	43.7	5.5
Ascending cycle 18, Aug. 1946–Jan. 1947	124	45	7.4
Ascending cycle 17, Nov.–Dec. 1935	171	36.9	4.6
Ascending cycle 14, Oct.–Nov. 1903	164	36.9	3.6
Ascending cycle 15, Aug. 1916–Jan. 1917	31	70	16.9
Entire RGO, May 1874–Oct. 2016	76	56.6	10.8

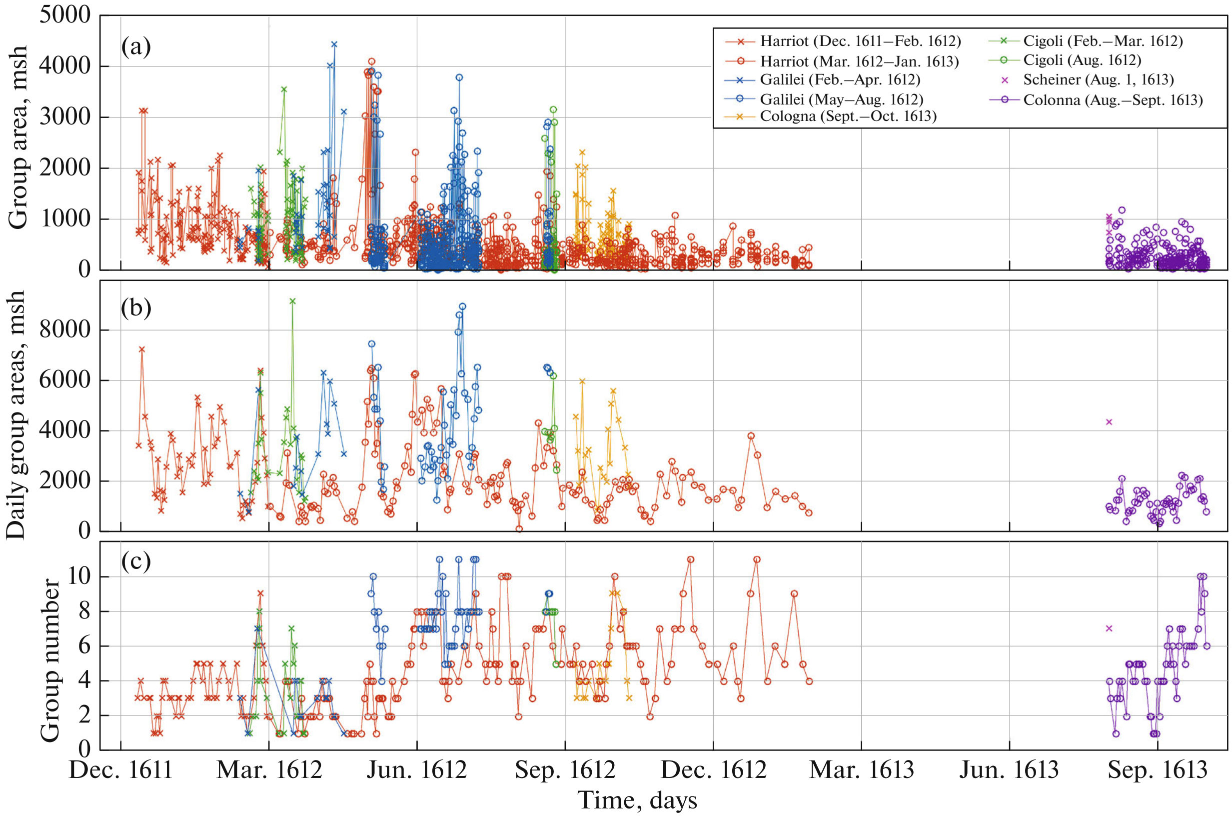

Fig. 2. (a) Area of individual sunspot groups, (b) daily total areas, and (c) daily numbers of sunspot groups reconstructed from observations by Harriot, Galilei, Cologna, Cigoli, Scheiner and Colonna. Circles mark solar parameters defined from detailed drawings, while crosses mark those from small schematic drawings.

groups. In Figure 1b, we show four observational intervals with the largest medians, those belonging to the ascending phase of cycles 14, 17, 18, and premaximum of cycle 19, and also one interval during the ascending phase of cycle 15 having the smallest median. We hypothesize that the historical abundance of sunspot groups should be similar to the modern one with a fraction of small groups of at least 35% and up to 70% during 1611–1613. In other words, we accept the hypothesis that the ratio of large and small spots in the seventeenth and twentieth centuries was similar. If so, then Harriot's reports might miss from ~30 to 60% of sunspot groups; Galilei's reports from ~20 to 55%. However note that Galilei's observations of February–April 1612 are schematic, the diameter of solar disks varies from 3.5 to 6 cm, while observations of May–August 1612 are of high quality and reproduce the fine structure of sunspot groups. Drawings by Cologna are all schematic, the diameter of the solar disks is less than 5 cm. While modern observations contain 15–20% of sunspot groups of an area from 101 to 200 msh, observations by Cologna only 7%. We evaluate that Cologna's reports might miss ~45–85% of sunspot groups. Most drawings by Cigoli are also schematic and might suffer from a deficit of ~35–70% of sunspot groups. Observations by Colonna demonstrate a larger portion of sunspot groups with an area 101–300 msh in comparison to the modern observations while missing ~20–50% of small groups. Here, finally, note that the cumulative impact of small sunspot groups to sunspot areas in modern observations (Table 1) varies from ~3.5 to 17% with an average of ~11% over the entire RGO.

For further analysis, we exclude few observations: Galilei 19 April–3 May 1612 (from Florence manuscripts), Cigoli 29 April–6 May 1612, and one drawing by Cologna on 10 September 1612, all due to large area uncertainty which exceeds factors of 1.5 and sometimes 2. Commonly, we suggest that the average uncertainty of sunspot area measurement is roughly 30% (Vokhmyanin et al., 2021).

Figure 2a shows the area of individual sunspot groups reported by Harriot, Galilei, Cologna, Cigoli, Scheiner, and Colonna from December 1611 to September 1613. Circles mark solar parameters defined from detailed drawings, while crosses mark those from small schematic drawings. The quality of Harriot's drawings gradually increases. Early observations (red crosses) lack small sunspots, but the later pattern of his observations (red circles) demonstrates a continuous majority of sunspot groups with an area less than 500 msh

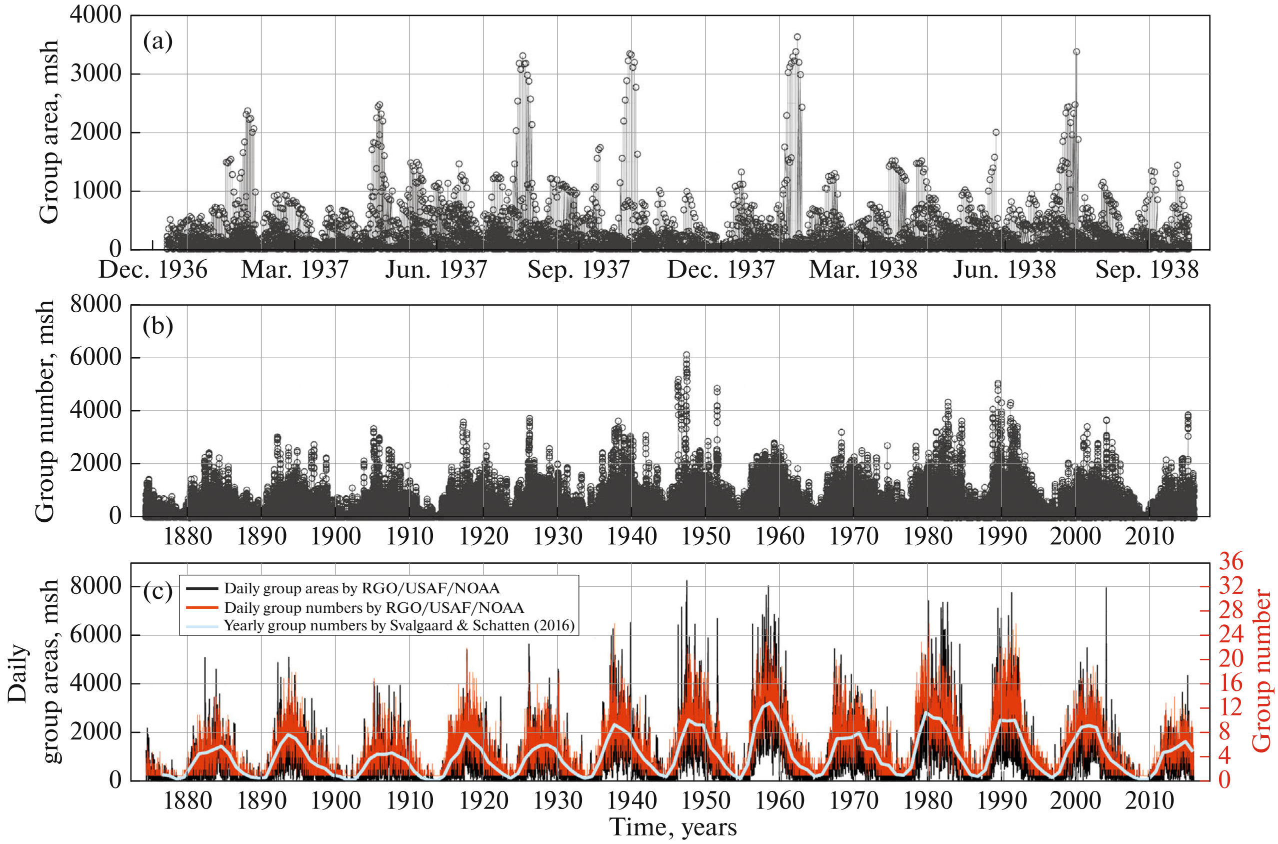

Fig. 3. (a) Area of individual sunspot groups near the maximum of cycle 17, (b) area of individual sunspot groups of the entire RGO/USAF/NOAA, and (c) daily group areas, daily group numbers and yearly mean group numbers by Svalgaard and Schatten (2016).

occasionally accompanied by the emergence of large sunspot groups of thousands of msh, up to 3000–4000 msh. A similar pattern is present in observations by Galilei and Cigoli. In August–September 1613, Colonna has drawn only one sunspot group with an area of more than 1000 msh, the majority of sunspot groups also has an area less than 500 msh.

Figure 2b shows daily total areas. Since sunspot parameters reconstructed from small schematic drawings (colored crosses) suffer from uncertainties resulting, for example, in the exaggeration of sunspots, hence their cumulative daily areas may give large values. Here, we will analyse data reconstructed from detailed drawings (circles). Observations by Harriot, Galilei, and Cigoli indicate that from May to August 1612 daily areas reach 6000 and even 8000 msh.

Figure 2c shows daily numbers of sunspot groups that reach 11 groups per day. Compare observations by Harriot and Cologna in September–October 1612. Both observers reported nearly the same number of sunspot groups (Fig. 2c), but the schematic style of small drawings by Cologna returns an enlarged area of sunspot groups (Fig. 1a).

Now, let us take a look at modern observations. Figure 3a shows the area of individual sunspot groups of an arbitrary chosen period near the maximum of cycle 17. One can ascertain a continuous majority of sunspot groups with an area less than 500 msh occasionally accompanied by the emergence of large sunspot groups of thousands of msh. This pattern is also inherent in other solar cycles. Recall that a similar structure was also revealed in Fig. 2a in historical observations.

Summarize, historical observations of 1611–1613 apparently belong to the ascending phase or maximum of a cycle, the area of individual sunspot groups reaches 3000–4000 msh (Fig. 2a), and daily areas reach 6000 and even 8000 msh (Fig. 2b). Let us find similar periods in modern data. Figure 3b shows the area of individual sunspot groups over the entire RGO period. Figure 3c contains daily group areas (black thin curve), daily group numbers (red thin curve), and yearly mean group numbers by Svalgaard and Schatten (2016) in light blue. The analogy to the declared solar parameters from historical data might be found at the beginning of the maximum of cycles 17–22, whose yearly mean group numbers varies between 9–13 groups.

4. DISCUSSION

Table 2 provides the number of observations per month (Fig. 4a) and the monthly mean group num-

Table 2. Monthly mean number of sunspot groups reconstructed from observations in 1611–1613, taking into account the minimum and maximum fraction of small sunspot groups which might be missing in historical drawings due to observational uncertainties

Observer	Data	Number of obs.	Monthly mean GN	GN + min fraction	GN + max fraction
Harriot	Dec. 1611	14	2.64	3.44	4.23
Harriot	Jan. 1612	18	3.5	4.55	5.6
Harriot	Feb. 1612	19	3.95	5.13	6.32
Harriot	Mar. 1612	15	2.27	2.95	3.63
Harriot	Apr. 1612	14	2.29	2.97	3.66
Harriot	May 1612	23	3.83	4.97	6.12
Harriot	Jun. 1612	14	5.86	7.61	9.37
Harriot	Jul. 1612	19	6.32	8.21	10.11
Harriot	Aug. 1612	14	5.64	7.34	9.03
Harriot	Sept. 1612	14	4.86	6.31	7.77
Harriot	Oct. 1612	13	5.38	7	8.62
Harriot	Nov. 1612	9	6.78	8.81	10.84
Harriot	Dec. 1612	7	6	7.8	9.6
Harriot	Jan. 1613	6	5.5	7.15	8.8
Galilei	Feb. 1612	3	3.67	4.4	5.68
Galilei	Mar. 1612	6	2.67	3.2	4.13
Galilei	Apr. 1612	6	2.83	3.4	4.39
Galilei	May 1612	9	7.22	8.67	11.19
Galilei	Jun. 1612	27	7.46	8.96	11.57
Galilei	Jul. 1612	8	8.63	10.35	13.37
Galilei	Aug. 1612	3	8.67	10.4	13.43
Cigoli	Feb. 1612	9	4.11	5.55	6.99
Cigoli	Mar. 1612	14	3.29	4.44	5.59
Cigoli	Aug. 1612	7	7.71	10.41	13.11
Cologna	Sept. 1612	16	4.5	6.52	8.33
Cologna	Oct. 1612	4	6	8.7	11.1
Colonna	Aug. 1613	25	3.52	4.22	5.28
Colonna	Sept. 1613	26	5.92	7.1	8.88

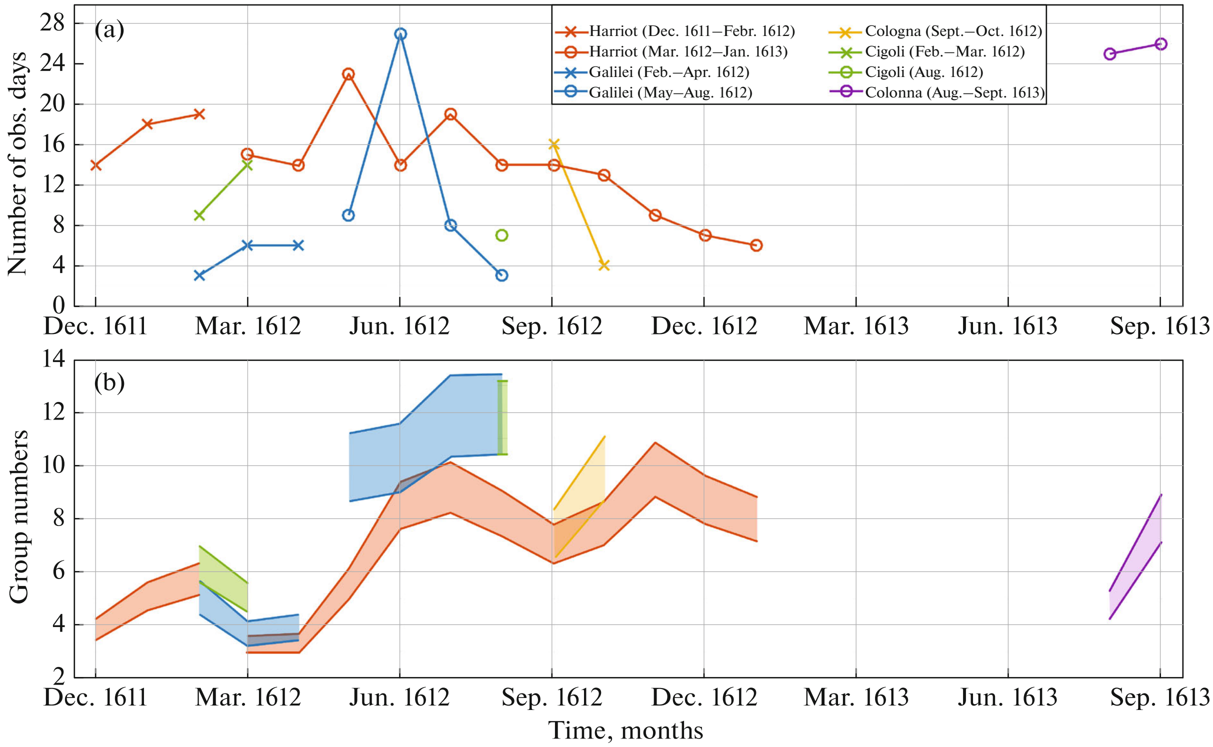

Fig. 4. (a) Number of observations per month in 1611–1613. Circles mark months with a better quality of drawings, while crosses mark those of poorer quality. (b) Estimated upper and lower activity levels, taking into account the minimum and maximum fraction of small sunspot groups which might be missing in historical drawings due to observational uncertainties.

bers in 1611–1613 for each observer. The two right-hand columns give the monthly mean group numbers taking into account the minimum and maximum fraction of small groups which might be missing in drawings due to observational uncertainties. These proposed levels of sunspot activity are shown in Fig. 4b. Recall that values of 1611 and the first third of 1612 (crosses in Fig. 4a) significantly suffer from observational uncertainties. Therefore, in fact, the activity level of that period is poorly defined. An average number of sunspot groups reported by Harriot from May 1612 to January 1613 is within 7.2–8 sunspot groups. 7.2 corresponds to the average group number plus the minimal fraction of small groups, while 8 is that plus the maximal fraction of small groups. Note that Harriot observed through clouds or misty air, the observation technique is unknown, penumbra and umbra were not resolved (Fig. 5, right column). In May–August 1612, employing projection technique Cigoli and Galilei made drawings reproducing the fine structure of sunspots (Fig. 5, left column) and returning 9.8–12.5 sunspot groups on average. Here, we hypothesize that period of 1612–1613 apparently belongs to the secular maximum. Of course, the estimates presented here are rather rough and do not take into account numerous uncertainties.

5. CONCLUSIONS

In this work, we process sunspot parameters reconstructed from historical observations by Harriot, Galilei, Cologna, Cigoli, Scheiner, Colonna, and Gassendi. The fractional distribution of sunspot group areas was exploited to evaluate the percentage of small groups of an area less than 100 msh. We hypothesise that the ratio of large and small spots in the seventeenth and twentieth centuries was similar. Basing the fact the modern observations of several months contain from ~35 to 70% of small sunspot groups, we extrapolated that Harriot's reports probably miss from ~30 to 60% of groups, Galilei ~20–55%, Cologna ~45–85%, Cigoli ~35–70%, and Colonna ~20–50%. Due to Gassendi's drawings lacking groups less than 300 msh, the fraction of missing sunspots can hardly be determined. Note, the estimates obtained agree with the uncertainty of the number of sunspot groups of the seventeenth century evaluated by Ogurtsov (2013).

Analysing time-series of the area of individual sunspot groups of historical and modern observations, we conclude that their structures are similar: a continuous majority of sunspot groups with an area less than 500 msh occasionally accompanied by the emergence of large sunspot groups of thousands of msh. Comparing daily group areas of historical and modern observations, we argue that the level of solar activity of

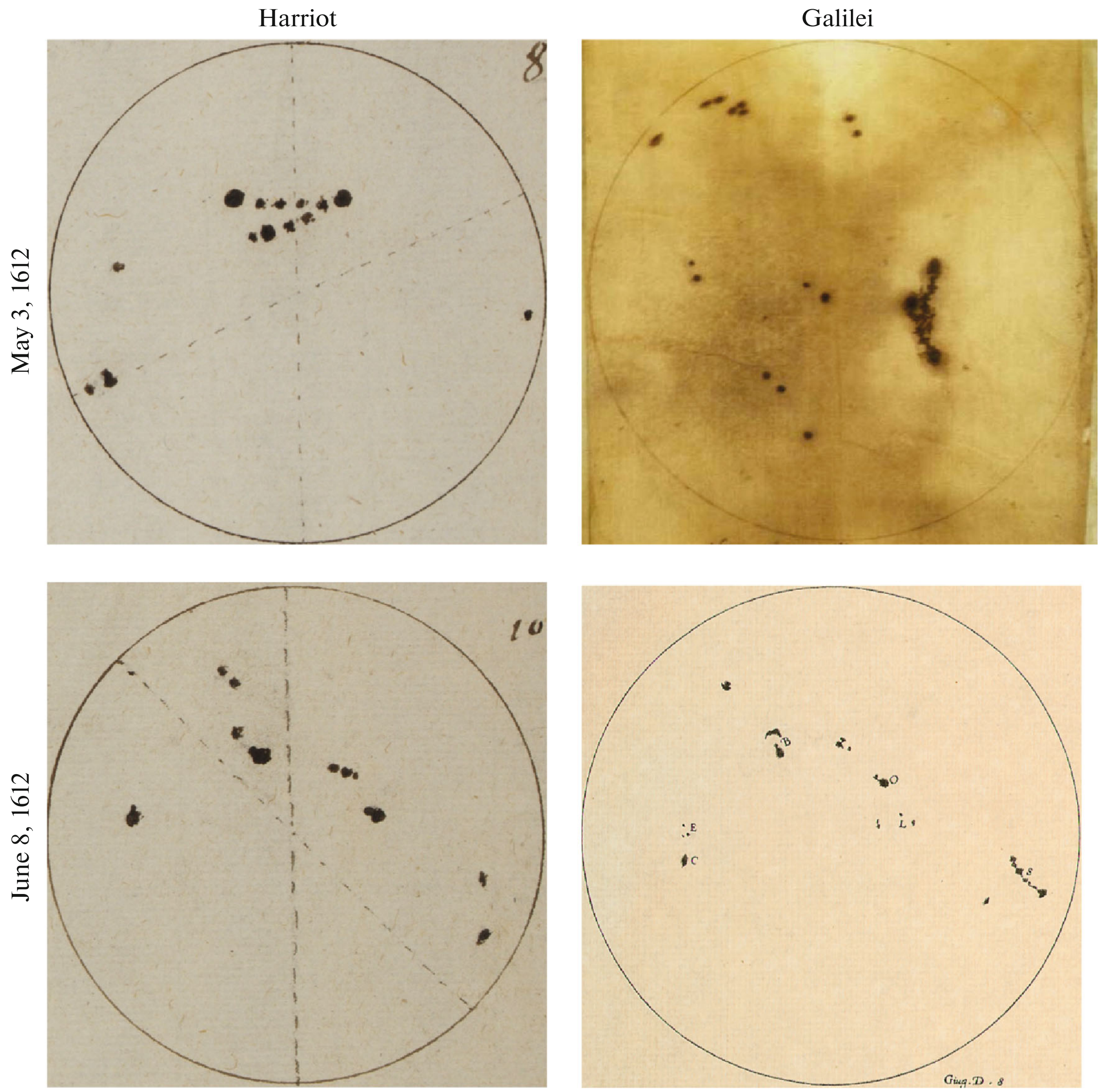

Fig. 5. Examples of sunspot drawings by Harriot (the Cultural Heritage Online, ECHO) and Galilei (Biblioteca Apostolica Vaticana and the Galileo Project by Al Van Helden and Owen Gingerich).

1611–1613 is compatible with that at the beginning of the maximum of cycles 17–19 and 21–22, whose yearly mean group numbers varies between 9–13 groups.

Finally, we evaluated the monthly mean group numbers taking into account the minimum and maximum fraction of small groups which might be missing in drawings of 1612–1613. We hypothesize that this period apparently belongs to the secular maximum.

We use the new Group Number series version 2.0 from WDC–SILSO (http://www.sidc.be/silso/groupnumber), data from the Royal Greenwich Observatory, United States Air Force, National Aeronautics and Space Administration (RGO/USAF/NOAA: solarscience.msfc.nasa.gov/greenwch.shtml), Harriot's drawings of sunspots from the Cultural Heritage Online (ECHO: echo.mpiwg-berlin.mpg.de/content/scientific_revolution/harriot/harriot_manuscripts), Galilei's drawings from the Manuscript Barb.lat.6479 of the Biblioteca Apostolica Vaticana (digi.vatlib.it/view/MSS_Barb.lat.6479/ 0053), and Galilei's drawings provided by the Galileo Project by Al Van Helden and Owen Gingerich (galileo.rice.edu).

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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