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REVISITED SUNSPOT DATA: A NEW SCENARIO FOR THE ONSET OF THE MAUNDER MINIMUM

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ABSTRACT

The Maunder minimum forms an archetype for the Grand minima, and detailed knowledge of its temporal development has important consequences for the solar dynamo theory dealing with long-term solar activity evolution. Here, we reconsider the current paradigm of the Grand minimum general scenario by using newly recovered sunspot observations by G. Marcgraf and revising some earlier uncertain data for the period 1636–1642, i.e., one solar cycle before the beginning of the Maunder minimum. The new and revised data dramatically change the magnitude of the sunspot cycle just before the Maunder minimum, from 60–70 down to about 20, implying a possibly gradual onset of the minimum with reduced activity started two cycles before it. This revised scenario of the Maunder minimum changes, through the paradigm for Grand solar/stellar activity minima, the observational constraint on the solar/stellar dynamo theories focused on long-term studies and occurrence of Grand minima.

Key words: dynamo – Sun: activity – sunspots

1. INTRODUCTION

The Sun is the only star whose features can be studied in great detail and on long timescale, forming a paradigm for a large population of "Sun-like" stars. The Sun exhibits a great deal of magnetic variability generically called the solar activity, which is grossly dominated by the quasi-periodic ≈11 year cycle. On top of that, secular variability is superposed ranging from very high activity during the late 20th century down to very quiet periods of Grand minima (Usoskin 2008; Hathaway 2010). Generally, the 11 year cyclicity is understood in terms of the solar dynamo (Charbonneau 2010), while the secular/millennial variability still remains unclear. A particular enigma for solar/stellar dynamo is the occurrence of Grand minima, which is not an intrinsic feature of the standard mean-field dynamo (Sokoloff 2004). Accordingly, the occurrence of Grand minima is often modeled by an ad hoc approach, including, e.g., stochastic or chaotic driven processes (e.g., Moss et al. 2008). Therefore, observational constraints on solar/stellar dynamo with respect to Grand minima are crucially important. While the statistic of Grand minima/maxima of solar activity is studied to some extent using the cosmogenic isotope data (Eddy 1977; Stuiver & Braziunas 1989; Usoskin et al. 2007; Abreu et al. 2008), the variability of solar activity during and around a Grand minimum is not precisely known. This is caused by the fact that presently we have more or less detailed information on only one Grand minimum—the Maunder minimum in the second half of 17th century (Eddy 1976; Soon & Yaskell 2003), which serves as an archetype for Grand minima in general. The present paradigm for a general scenario of a Grand minimum (see Usoskin & Mursula 2003, and references therein) is widely considered as a constraint for solar dynamo models. Therefore, every piece of information on solar activity during that period is extremely valuable.

Temporal variability of solar activity around the Maunder minimum is usually studied using historical telescopic observations of sunspots since 1610 (Vaquero & Vázquez 2009). The period before the Maunder minimum (i.e., the first half of the 17th century) was very uncertain in the original Wolf sunspot series, but the data were greatly improved after tremendous work of Hoyt et al. (1994) and Hoyt & Schatten (1998), who collected large amount of historical sunspot records, forming the group sunspot number (GSN) series. The solar activity variability before 1650 AD is shown in Figure 1 according to the official GSN series (dotted curve) and reanalyzed with improved statistical techniques (Usoskin et al. 2003; gray curve). The first observed solar cycle 1610–1618 was pretty high (maximum annual GSN values above 100), and this is quite reliable as it was covered by the direct data including sunspot drawings and counts (Hoyt & Schatten 1998). The second cycle 1618–1630 was lower (maximum GSN values 30–40), but the quality of data is not good. The next cycle 1635–1645 is marked as high in the GSN series, and this gave rise to the idea of an abrupt onset of the general Grand minimum scenario.

However, the GSN series is also not complete, and new data, which remained unnoticed by Wolf and his successors including Hoyt & Schatten, are continuously recovered in various places, often outside major observatories (Arlt 2008, 2009; Casas et al. 2006; Vaquero 2004; Vaquero et al. 2005, 2007a). This leads to a revision of some parts of the GSN series and requires reanalysis of some results. Here we reconsider the paradigm of a Grand minimum general scenario by using newly recovered sunspot observations as well as revising some earlier uncertain data for the period 1636–1642, i.e., one solar cycle before the beginning of the Maunder minimum.

2. REVISED SUNSPOT DATA FOR 1636–1642

As discussed in great detail by Vaquero (2007b), sunspot data in 1610–1644 (before the Maunder minimum) contain numerous gaps and uncertainties. This problem is especially acute for the period from 1636 through 1642. For that period the following data sets were available in the GSN series: (1) three years (1636, 1637, and 1641) without any solar observational record; (2) two years (1640 and 1642) with little amount of records by Horrox, Gassendi, Hevelius, Scheiner, and Rheita (2 and 37, respectively); and (3) two years (1638 and 1639) with estimated data based on Crabtree data. Here we use the GSN database[4], but critically revise it for 1636–1642.

[4] ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/GROUP_SUNSPOT_NUMBERS/

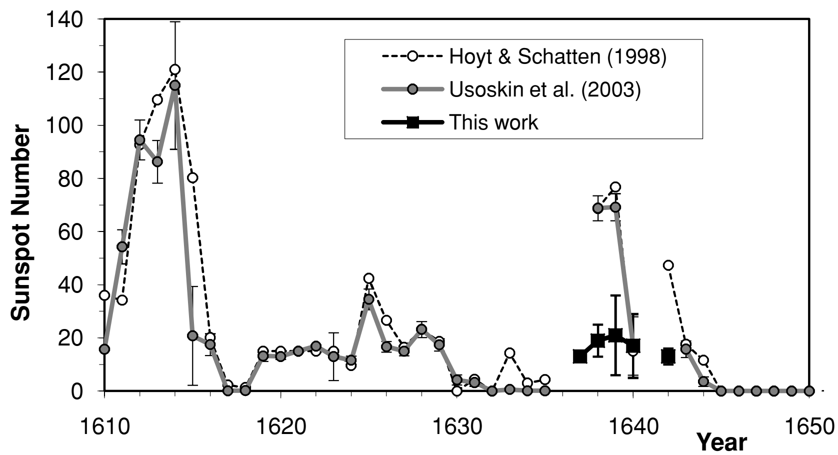

Figure 1. Annual sunspot numbers in the first half of 17th century. Group sunspot numbers R_g (Hoyt & Schatten 1998) are shown by the dotted line, weighted sunspot number, based on the same data set (Usoskin et al. 2003) by the gray line, and the weighted sunspot number R_w estimated in this work by the black line.

First, we add newly recovered sunspot data by G. Marcgraf which are not included into the GSN database. Georg Marcgraf (1610–1644) was a German naturalist and astronomer (North 1989). We have consulted his manuscripts of astronomical observations preserved in Leiden Regional Archive (Collection Marcgraf LB7000/1) and in the National Library of Portugal (Mss. 6, no. 37). We have recovered sunspot records for the year 1637, just the year with no records in the GSN database. These records are preserved in the "Collection Marcgraf" (Leiden Regional Archive, LB7000/1) in the documents labeled as 22, 24a, 24b, and 52 according to the numeration made by the historian of science John North in the 1980s (North 1989). Figure 2 depicts an example of solar disk drawings by Marcgraf showing one sunspot from 1637 June 9 to 12 (document 24a). Sunspot records by Marcgraf cover 17 days of 1637 that were included in the new database (see Table 1).

Another addition is the correction of Horrox's records. Jeremiah Horrocks or Horrox (1618–1641) was an English astronomer who predicted, observed, and recorded the transit of Venus in 1639. His sunspot records appeared in his "Opera Posthuma" (Horroccii 1673). Horrox used the Julian Calendar and, therefore, we have converted these dates to Gregorian Calendar (Vaquero 2007b). Moreover, Horrox noted "Maculae duas in Sole" (two spots in the Sun) on 1638 October 30–November 1. We have interpreted these two spots as one sunspot group to make this record compatible with the only group observed by Gassendi on the same dates.

Next we noted that the filling of the years 1638 and 1639 in the GSN was done based on an unclear estimate rather than on real data. Hoyt & Schatten (1998) wrote in their Bibliography appendix: "According to a letter by Crabtree the average number of spot groups seen in 1638 and 1639 was 4–5 per day. The database has Greenwich fill values to give 4–5 groups per day. This substitution technique was used to simplify the analysis. This is the only place in the entire database where we do this type of substitution." However, the number of the actually observed groups was smaller than the number of estimated groups for these years in the reconstruction (see Figure 5 in Vaquero 2007b). Therefore, we decided not to use these non-observed values for our estimations and eliminate Crabtree data.

We have also made some minor corrections to the database using the original sources. We have eliminated one spurious observation by Gassendi on 1638 December 1, because this record does not appear in his astronomical observations (Gassendi 1658). Moreover, we have incorporated one sunspot record by Horrox in 1639 December 4. Curiously, the treatise "Venus in sole visa" (Venus in transit across the Sun) by Horrox was published by Johannes Hevelius at his own expense in 1662 (Hevelius 1662). In this work, Horrox noted that he saw one small and common spot in the Sun on 1639 December 4 (p. 115 of Hevelius 1662). Finally, we have also changed the record by Rheita in 1642 using the original source (pp. 242–243 of Rheita 1645).

All these additions and changes in the original Hoyt and Schatten database are listed in Table 1 and summarized below.

Table 1
Sunspot Observations (Date, Number of Sunspot Groups G, and the Observer) for 1636–1642 Used in This Stay

Date	G	Observers	Comment
1637 Jan 19–20	1	Marcgraf	New data
1637 Jan 22	0	Marcgraf	New data
1637 Feb 5	1	Marcgraf	New data
1637 Jun 9–12	1	Marcgraf	New data
1637 Jun 13	0	Marcgraf	New data
1637 Sep 21	2	Marcgraf	New data
1637 Sep 24–25	2	Marcgraf	New data
1637 Sep 28	0	Marcgraf	New data
1637 Oct 10	0	Marcgraf	New data
1637 Oct 12–13	1	Marcgraf	New data
1637 Oct 15	0	Marcgraf	New data
1638 Jun 1–3	2	Horrox	Corrected date
1638 Oct 29	0	Gassendi	HS98
1638 Oct 30–Nov 1	1	Horrox	Corrected date and G
1638 Oct 30–Nov 1	1	Gassendi	HS98
1639 Dec 4	1	Horrox	New data
1640 Aug 21–22	1	Scheiner	HS98
1642 Jun 9–22	1	Rheita	Corrected date and G
1642 Oct 26	0	Hevelius	HS98
1642 Oct 28	1	Hevelius	HS98
1642 Oct 31–Nov 1	1	Hevelius	HS98
1642 Nov 3–4	1	Hevelius	HS98
1642 Nov 6	3	Hevelius	HS98
1642 Nov 8	2	Hevelius	HS98
1642 Nov 9 and 11–17	1	Hevelius	HS98
1642 Nov 18	0	Hevelius	HS98

Note. The last column comments on the relation of the observation to the HS98 (Hoyt & Schatten 1998) database.

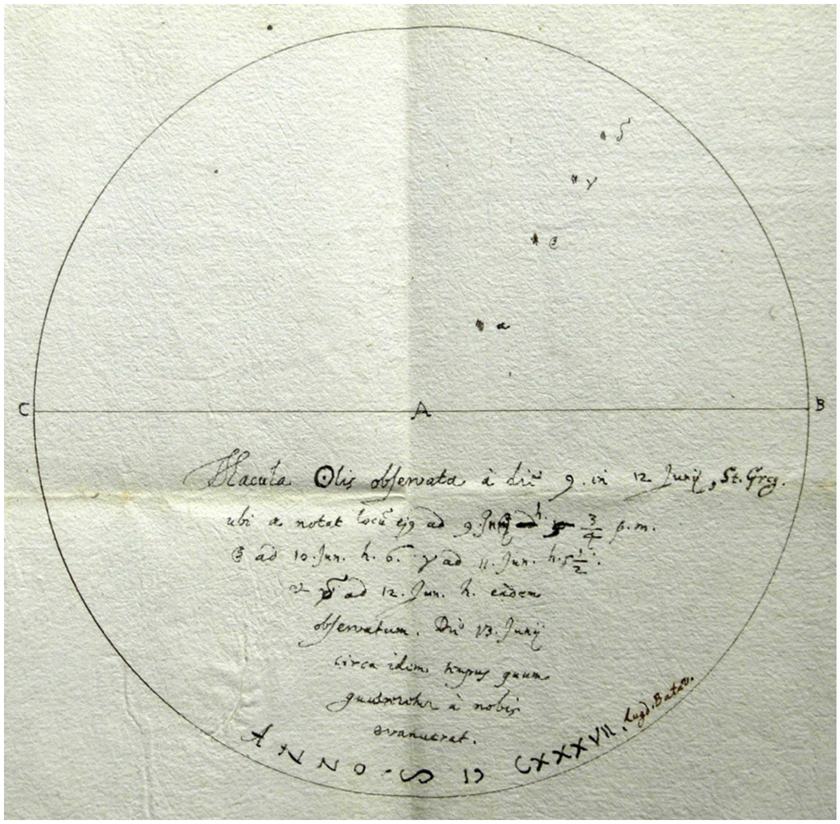

Figure 2. Example of the solar disk drawing by Marcgraft depicting one sunspot from 1637 June 9 to 12.

1. Newly recovered sunspot records by G. Marcgraf are added.
2. The estimated (not observed) values from Crabtree's comments (1638–1639) are discarded.
3. Dates and numbers of sunspot groups are corrected for Horrox's observations.
4. A spurious observation by Gassendi on 1638 December 1 is eliminated.
5. One missing sunspot record by Horrox in 1639 December 4 is added.
6. The record by Rheita in 1642 is corrected.

Using the revised data presented in Table 1, we have evaluated the annual sunspot numbers for the period of 1637–1642, employing the statistical method proposed by Usoskin et al. (2003). The method is based on comparing the actual sparse data (sample population) to the daily sunspot data in 1850–1996 (reference population), assuming constancy of the statistical properties of sunspot activity. For a given sample population of daily measurements within a month, months in the reference population are found that contain the same subset of daily values. A statistical distribution of the corresponding monthly means is then built so as to allow the estimation of the mean and uncertainty of monthly sunspot numbers, reconstructed from sparse daily observations (see full details in Usoskin et al. 2003). From monthly mean values, yearly values can be obtained in the same way. The newly computed yearly sunspot numbers for 1637–1642 are given in Table 2 and shown in Figure 1 as thick solid line with error bars.

As one can see from Figure 1, the revised and updated data for 1637–1642 have essentially changed the profile of temporal variability of sunspot data before the Maunder minimum. In particular, the last solar cycle before the minimum now appears quite modest, with the peak value of 21 ± 15 compared with about 70 in the GSN series. The new scenario, in accordance with the new database, implies low solar activity roughly two solar cycles before the beginning of the Maunder minimum. This suggests that transition from the normal activity to the deep minimum was not as sudden as previously thought (Usoskin 2008), and the descent of solar activity might have started as early as in the 1610s.

Table 2
Yearly Group Sunspot Numbers for 1637–1642: Formal Values R_g (Hoyt & Schatten 1998) as well as the Calculated Here Weighted Values R_w with $\pm\sigma$ Uncertainties

Year	R_g	R_w
1637	n.a.	13 ± 2
1638	68.7	19 ± 6
1639	76.8	21 ± 15
1640	15	17 ± 12
1641	n.a.	n.a.
1642	47.3	13 ± 3

3. DISCUSSION AND CONCLUSIONS

Since the Maunder minimum forms an archetype for the Grand minima, detailed knowledge of its temporal development has important consequences for the solar dynamo theory dealing with long-term solar activity evolution. The general dynamo theory (see, e.g., Charbonneau 2010) cannot naturally reproduce the occurrence of Grand minima and requires some prescribed changes in the dynamo parameters. The present paradigm for the Maunder minimum (e.g., Vitinsky et al. 1986; Sokoloff & Nesme-Ribes 1994; Frick et al. 1997; Usoskin et al. 2000; Soon & Yaskell 2003; Usoskin 2008) is that transition from the normal high activity to the deep minimum was sudden (within a few years) and without any apparent precursor, while the recovery to the normal activity level was gradual, taking several decades. The abrupt onset of a Grand minimum forms a strong constraint, as only few models with stochastically driving forces can "naturally" produce such a feature (e.g., Charbonneau & Dikpati 2000), while others require special ad hoc assumptions. Presently, several models can reproduce, with different approaches, the proposed scenario of a Grand minimum (e.g., Charbonneau & Dikpati 2000; Charbonneau et al. 2004; Usoskin et al. 2009b; Karak 2010; Passos & Lopes 2011).

On the other hand, many dynamo models succeed in predicting Grand minima to start gradually, through a continuous decrease of the activity level to the deep minimum, followed by a gradual recovery. Just to mention a few, Küker et al. (1999), Weiss & Tobias (2000), Brooke et al. (2002), Bushby (2006), and Moss et al. (2008). Thus, it is crucial to know the solar activity evolution before the Maunder minimum with high confidence.

The revised sunspot records presented here imply that the scenario of the Maunder minimum can correspond to a gradual onset, contrary to the earlier consideration, thus affecting observational constraints on the solar/stellar dynamo. Unfortunately, cosmogenic isotope data can hardly resolve individual cycles (Steig et al. 1996; Usoskin et al. 2009a) to clearly answer this question, but a cautious statistical study of radiocarbon ^{14}C data in tree rings for the Maunder and Spörer solar minima indicates a possible lengthening and attenuation of solar cycles a few decades before the onset of a Grand minimum (Miyahara et al. 2008).

The major findings of this work can be summarized as follows.

1. Using newly recovered sunspot records by Georg Marcgraf and carefully revised data for other observations (Table 1), we provide a new sunspot number series (Table 2) for the period 1636–1642.
2. The new data dramatically change the magnitude of the sunspot cycle just before the Maunder minimum, from 60–70 down to about 20, implying a possibly gradual onset of the minimum with reduced activity started two cycles before it.
3. This revised scenario of the Maunder minimum changes, through the paradigm for Grand solar/stellar activity minima, the observational constraint on the solar/stellar dynamo theories focused on long-term studies and occurrence of Grand minima.

Thus, we have essentially revised the sunspot data prior to the Maunder minimum leading to the revisited observational scenario of a Grand minimum of solar activity. The present results are expected to impact development of models dealing with long-term solar/stellar activity evolution.

All the historical materials used in this work were consulted at the Regionaal Archief (Leiden, Netherlands), Biblioteca Nacional de Portugal (Lisbon, Portugal), and Biblioteca del Real Observatorio de la Marina (San Fernando, Spain). Support from the Junta de Extremadura and Ministerio de Ciencia e Innovación of the Spanish Government (AYA2008-04864/AYA) is gratefully acknowledged. G.A.K. acknowledges visiting grant from the Finnish Academy.

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