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RESEARCH

No Evidence for Absence of Solar Dynamo Synchronization

F. Stefani[1] · J. Beer[2] · T. Weier[1]

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Abstract
The old question of whether the solar dynamo is synchronized by the tidal forces of the orbiting planets has recently received renewed interest, both from the viewpoint of historical data analysis and in terms of theoretical and numerical modeling. We aim to contribute to the solution of this longstanding puzzle by analyzing cosmogenic radionuclide data from the last millennium. We reconsider a recent time series of ^{14}C-inferred sunspot data and compare the resulting cycle minima and maxima with the corresponding conventional series down to 1610 A.D., enhanced by Schove's data before that time. We find that, despite recent claims to the contrary, the ^{14}C-inferred sunspot data are well compatible with a synchronized solar dynamo, exhibiting a relatively phase-stable period of 11.07 years, which points to a synchronizing role of the spring tides of the Venus-Earth-Jupiter system.

Keywords Solar cycle models · Solar cycle observations

1. Introduction

The question of whether the solar dynamo might be "clocked" by the motion of the planets traces back to early speculations by Wolf (1859) and has popped up sporadically ever since (de la Rue, Stewart, and Loewy, 1872; Bollinger, 1952; Jose, 1965; Takahashi, 1968; Wood, 1972; De Jager and Versteegh, 2005; Callebaut, de Jager, and Duhau, 2012). Recently, new impetus was given to the issue by the exemplification of Hung (2007), Scafetta (2012), Wilson (2013), and Okhlopkov (2016) that the 11.07-year spring-tide period of the tidally dominant planets Venus, Earth, and Jupiter appears to be in a phase-stable relation with the solar cycle. This finding turned out to be in amazing agreement with the older results of Schove's ambitious "spectrum of time" project (Schove, 1983) to determine the solar-cycle maxima and minima for the last two and a half millennia mainly from historical *aurora borealis* sightings and naked-eye sunspot observations. Furthermore, the identified 11.07-year periodicity is also, within error margins, well compatible with the phase-stable 11.04-year cycle as inferred by Vos et al. (2004) utilizing two different algae data-sets from the early Holocene.

✉ F. Stefani
F.Stefani@hzdr.de

1 Helmholtz-Zentrum Dresden – Rossendorf, Bautzner Landstr. 400, D-01328 Dresden, Germany

2 Eawag, Überlandstrasse 133, 8600 Dübendorf, Switzerland

The key problem with those observed correlations is how they could be substantiated by any viable kind of causation. While the tidal forces of the planets are customarily ridiculed by the minuscule tidal height of the order of 1 mm, several physical mechanisms have been invoked that could possibly lead to noticeable effects, among them the extreme sensitivity of the storage capacity for magnetic fields in the sub-adiabatic tachocline (Abreu et al., 2012; Charbonneau, 2022) or the susceptibility of intrinsic helicity oscillations of waves or instabilities (in particular, the Tayler instability) to tidal forces (Weber et al., 2013, 2015; Stefani et al., 2016; Stefani, Giesecke, and Weier, 2019; Stefani et al., 2020a; Stefani, Stepanov, and Weier, 2021).

Going beyond such mainly qualitative arguments, Horstmann et al. (2023) have recently shown that even weak tidal forces such as those of Jupiter might excite (magneto)-Rossby waves with typical velocity amplitudes up to the order of $\mathrm{m\,s^{-1}}$. A concurrent 2-dimensional simulation by Klevs, Stefani, and Jouve (2023) affirmed that tidally triggered oscillations of the tachoclinic α-effect of the order of $\mathrm{dm\,s^{-1}}$ would be sufficient to synchronize an otherwise conventional $\alpha - \Omega$-dynamo model. Together with the older argument of Öpik (1972) that the "ridiculous" 1 mm tidal height corresponds energetically to a velocity scale of $1\ \mathrm{m\,s^{-1}}$, those recent results suggest that tidal forces may entail a serious potential for solar dynamo synchronization.

Yet, a hard-to-solve problem of that kind would not even appear if the solar dynamo was not phase-stable in the first place. Two recent papers (Nataf, 2022; Weisshaar, Cameron, and Schüssler, 2023) have seriously put into question the empirical evidence for phase-stability. Ignoring the strong argument in favor of phase stability coming from the algae-date of the early Holocene (Vos et al., 2004), both papers focused exclusively on the series of solar-cycle extrema (i.e., minima or maxima) during the last millennium. Nataf (2022) dismissed all the meticulous efforts of Schove (1983) by claiming his cycle reconstruction to be "finagled" by simple rules. Strictly presupposing that the solar cycle *is not* clocked, he argued that Schove's "nine-per-century" rule would lead to a constrained and, therefore, wrong series of extrema. What was not considered by Nataf (2022), though, was the possibility that the solar cycle *might indeed be* clocked by an 11.07-year trigger, in which case Schove's *auxiliary* "nine-per-century" rule would do absolutely no harm to an otherwise correctly inferred series of extrema. In this respect, it is interesting to note that Schove's data actually point to an average Schwabe cycle of 11.07 years rather than the 11.11-year one, which would result from a naive application of the "nine-per century" rule (see Figure 1 of Stefani et al. 2020a). For further critical remarks on Nataf (2022), see the recent comment by Scafetta (2023) and the response to it by Nataf (2023).

The second paper that claims to have finally debunked the clocking scenario was recently published by Weisshaar, Cameron, and Schüssler (2023). Based on ^{14}C data of Brehm et al. (2021) for the last millennium, it uses the series of cycle extrema inferred by Usoskin et al. (2021) to show that this series points - with a high statistical significance - to a random walk process instead of a clocked process.

In the present paper, we will reanalyze this series of cycle minima and maxima and compare it with another series of extrema for which we use a combination of the standard Schwabe cycles for the later time interval starting at 1610 with Schove's data (Schove, 1983) for earlier times. We will show that - for the most part of the interval - the extrema of both series can uniquely be matched one-to-another with three exceptions. The latest shows up around 1840, where Usoskin's data exhibit two shallow minima at a place where the telescopic data show only one. Given the shallowness of these two minima, and the relatively low-quality flag of the first one, we find it legitimate to replace this pair with only one minimum and to cancel the corresponding maximum between them. A second ambiguity is found amidst the Maunder minimum around 1650 where all quality flags of Usoskin's data are relatively low. Here, again, we tentatively cancel one shallow minimum. The most problematic part appears in the interval between 1040 and 1140, where Usoskin's quality flags are generally quite low. Specifically, we consider three different ways of correcting the data, which we all consider at least as plausible as the original selection of Usoskin et al. (2021).

Then we will analyze the considered time series with view on their phase stability. At first, we show the respective "Observed-Minus-Calculated" (O-C) diagrams of the residuals of the instants of the minima from a theoretical linear trend with an alleged 11.07-year period. While the Schove/NOAA data are concentrated around a horizontal line with only slight ($\pm$ 4 years) upward or downward deviations, Usoskin's data show larger deviations exactly within the three problematic intervals discussed above. We show how these deviations are consecutively reduced by our corrections. Thereby, we arrive at a one-to-one matching of the ^{14}C extrema with those of the Schove/NOAA series for the entire 9 century long interval.

In the last step, we compute - for the different time series - Dicke's ratio between the standard deviation of the residuals and the standard deviation of the differences between neighbouring residuals. A closely related measure, defined by Gough (1981), was used by Weisshaar, Cameron, and Schüssler (2023) and Biswas et al. (2023) to argue in favor of a random walk process. We show here that already the two highly plausible corrections around 1840 and 1650 lead to a dramatic move of either of the two ratios towards the corresponding theoretical curve for a clocked process. Finally, we show that a good deal of the remaining deviations from a strictly clocked curve turns out to be due to the presence of a well-expressed Suess-de Vries cycle in the data.

The paper closes with some conclusions.

2. Data Sets and Possible Corrections

In the following, we will discuss two data sets. The first one is the annual series of (pseudo) sunspot numbers as recently inferred by Usoskin et al. (2021) from the ^{14}C production rate data of Brehm et al. (2021). To start with, we simply adopt the cycle minima and maxima as derived by Usoskin et al. (2021).

The second series of minima and maxima consists of the standard data provided by NOAA (www.ngdc.noaa.gov/stp/solar/solardataservices.html) with the starting year 1610, merged with the earlier data as published by Schove (1983) and partly corrected in Schove (1984).

In Figure 1, these data are presented in five 250-year intervals, with 25-year overlaps at each beginning and end. The size of the symbols of Usoskin's minima (green open circles) and maxima (red open circles) is scaled by the so-called "quality flag" between $q = 0$ ("cycle cannot be reliably identified") till $q = 5$ ("clear cycle in both shape and amplitude"). The violet line depicts the (pseudo) sunspot number according to Usoskin et al. (2021), where, in most cases, the attribution to the minima and maxima is rather clear. Two evident exceptions occur for the maxima at 1435 and 1468, which are obviously due to typing errors in Table 1 of Usoskin et al. (2021), and which we correct, according to the ^{14}C-curve (violet dashed lines in the middle panel of Figure 1) to the years 1425 and 1461, respectively.

The red and green open squares at the upper and lower abscissa depict the Schove/NOAA maxima and minima, respectively. After the two trivial corrections mentioned above, we obtain a sequence of one-to-one matches between the 44 minima and maxima of Usoskin

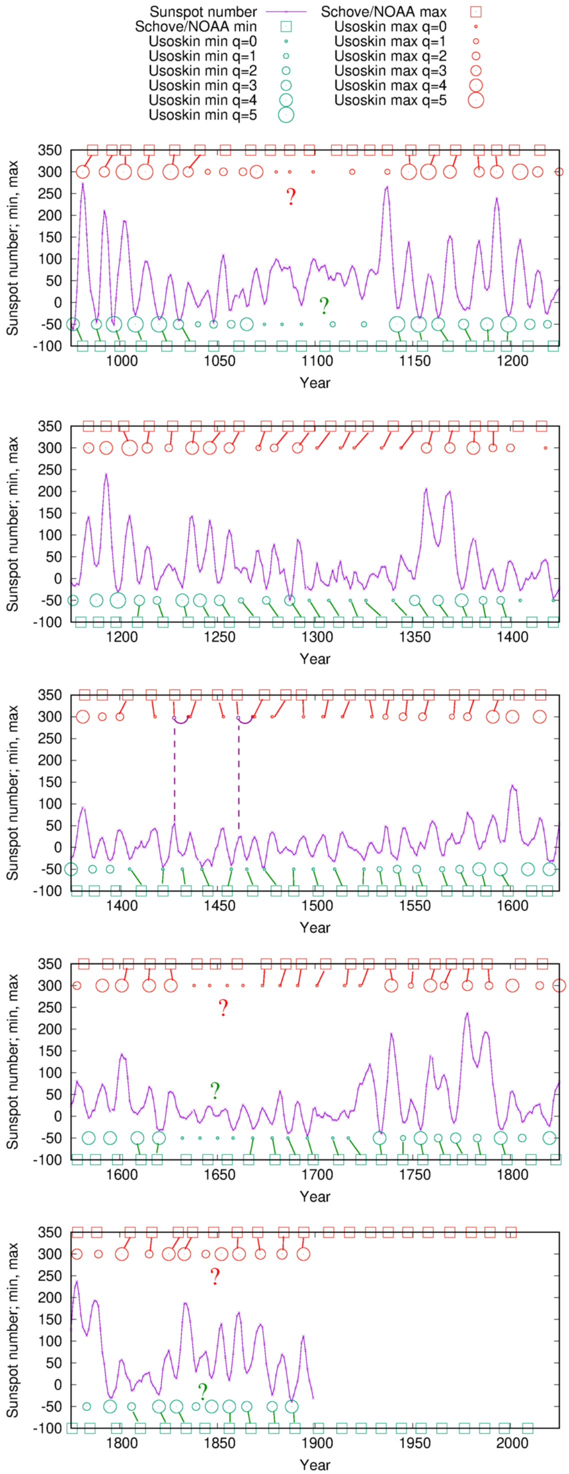

Figure 1 Annual (pseudo) sunspot numbers (*violet lines*) between 975 and 1895, and inferred solar cycle maxima (*red circles*) and minima (green circles) from Usoskin et al. (2021), together with the maxima (*red squares*) and minima (*green squares*) from Schove (1983) and NOAA. Each panel shows a period of 250 years, with overlapping intervals of 25 years. *Red and green thin lines* indicate putative correspondences between the respective extrema. The size of the *red and green circles* mirrors the quality flag q according to Usoskin et al. (2021) (smallest *circles* denote very poor quality, $q = 0$, largest *circles* denote highest quality, $q = 5$). *Red and green question marks* point to intervals with unclear correspondences, typically at times with low-quality flags. Two *dashed violet lines* around 1425 and 1461 indicate corrections of obvious typing errors for the maxima in Table 1 of Usoskin et al. (2021).

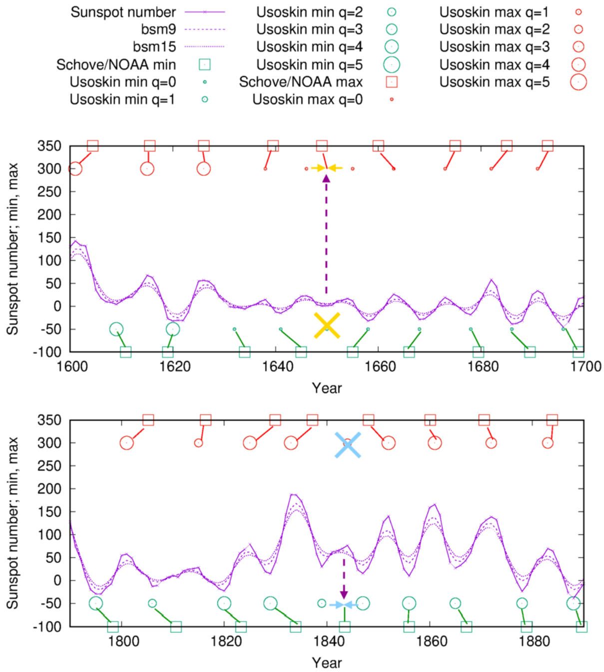

Figure 2 Plausible corrections of minima/maxima in two late time intervals. Symbols and lines as in Figure 1, except that two binomially filtered curves bsm 9 (including 9 coefficients, *dashed violet*) and bsm 15 (including 15 coefficients, *dotted violet*) are added to the original ^{14}C data (*violet full line*). Lower panel: Interval from 1790 till 1890. The filtered curves suggest that the two minima at 1839 (with a low-quality flag of $q = 2$) and 1846 might indeed represent only one minimum at 1843 which would also better fit to the observational data. The merging of the minima is indicated by two *horizontal light-blue arrows*, the cancellation of the maxima between them by a corresponding *light-blue cross*. Upper panel: Interval between 1600 and 1700. Here, amidst the Maunder minimum, the quality flags of the minima and maxima are typically low, making their unambiguous identification quite hard. A most plausible cancellation of a flat minimum is indicated by a *yellow cross*.

and Schove/NOAA that stretches uninterruptedly over the time interval between 1140 and 1620.

Evidently, there are three distinctive segments where this one-to-one correspondence fails or at least becomes problematic. The first one concerns the long interval between 1040 and 1140, the second one is situated around 1650, the third one around 1840.

In Figure 2, we consider two particular segments in more detail. Let us start with the latest part, around 1840, which is shown in the lower panel of Figure 2. Evidently, the NOAA data comprise only one minimum at 1843.5, whereas Usoskin's data show two minima here, at 1839 and 1847, the former of which having a relatively low-quality flag of $q = 2$. In order to shed more light on this issue, we add to the original violet curve of sunspot data two further curves representing two different binomial smoothings (bsm 9 and bsm 15) that tend to smear out the two shallow minima into a single one centered at 1843, which indeed corresponds to the NOAA value. Given the high validity of the observationally constrained cycles in the middle of the 19th century, we consider such contraction of two minima into a single one (indicated by the two light-blue arrows) and the corresponding cancellation (light-blue cross) of one maximum as highly plausible.

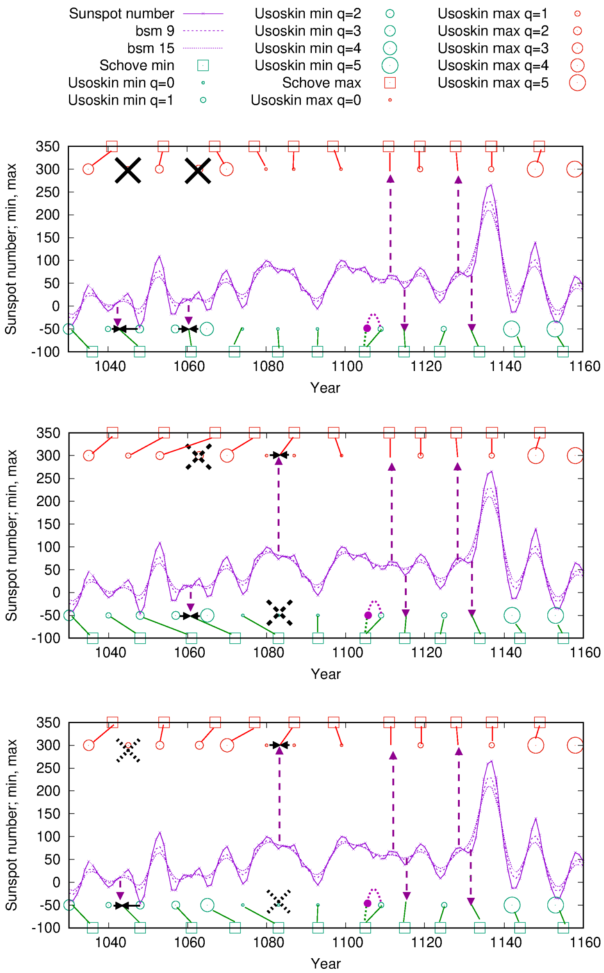

Figure 3 As Figure 2, but for the early interval between 1030 and 1160. The *vertical violet lines* indicate the insertion of two minima/maxima pairs in the later segment of that interval. The *black horizontal arrows and crosses* indicate contractions and cancellations of various minima or maxima in the early segment of the interval of which we show three different permutations indicated by *full, dashed,* and *dotted* types of *black crosses*.

Next we turn to the situation around 1645 (upper panel in Figure 2). Here, amidst the Maunder minimum, we should have less trust into the NOAA data (as for the problem of interpretation of naked-eye sunspot observations during this time, see Carrasco et al. 2020). Hence, it is not excluded that the additional minimum/maximum pair of Usoskin's data is indeed a real one. This possibility will be discussed below. Still, it is also plausible that Usoskin's data show one minimum/maximum pair too much. From the most evident variants to contract either the two (flat) maxima at 1638 and 1646 or those at 1646 and 1655, we show only the latter one, indicated with yellow arrows, together with the canceled minimum at 1650 (yellow cross).

Finally, we treat, in Figure 3, the long period between 1040 and 1140. This interval, which strongly overlaps with the Oort minimum, is characterized by a large number of low-quality flags. While the total number of minimum/maximum pairs in this segment is the same for the data of Usoskin and Schove, we immediately notice the presence of two extremely long neighboring cycles between the maxima at 1099 and 1119 (20 years) and 1119 and 1137 (18 years). In either of those intervals, we observe the existence of one (or two) local minimum/maximum pair(s). Without overemphasizing the validity of Schove's data (although the corresponding maxima were not labeled as uncertain by him, in contrast to many others in Schove, 1983), we see at least that an insertion of the two additional maximum/minimum pairs (indicated by the violet arrows) leads to a one-to-one match of the extrema of both data sets. Yet, the insertion of the first maximum leads to an even greater uncertainty for the minimum just before it, which might well shift from its place at 1109 (according to Usoskin) to some position before. This variant is indicated by the bent dotted violet curve ending in the alternative minimum at 1104 (violet full circle).

Even more uncertain than in this late segment of the 1040 – 1140 interval is the situation in the early segment, which contains quite a number of low-q extrema, leading to a significant number of possible permutations of minimum/maximum pairs, in addition to those chosen by Usoskin et al. (2021). In order to "make good" for the two *insertions* in the later segment, we opted here for a compensating *cancellation* of two minima/maxima pairs in the early segment, a choice that is, admittedly, strongly debatable. The different panels in Figure 3 illustrate three most plausible permutations of minimum/maximum cancellations in this early segment. The corresponding contractions or cancellations are indicated by black arrows and three types of black crosses (full, dashed, dotted). While in all three cases, we obtain a one-to-one match of the resulting minimum/maximum pairs with those of Schove, the first and third variants (with the full and dotted crosses) lead to the most plausible correspondences.

3. O-C Plots, Dicke's Ratio, and the Influence of the Suess-de Vries Cycle

A first qualitative hint for phase-stability, or its absence, can be gained from the so-called "Observed-Minus-Calculated" (O-C) diagram whose suitability for solar-cycle analyses was advocated by Richards et al. (2009). It shows the differences (or residuals) of a given data set from a linear trend for which we use here an alleged 11.07-year period of the Schwabe cycle. The lowermost green curve (with open squares) in Figure 4 shows the residuals for the combined Schove/NOAA minima. Evidently, they are wiggling around a rather horizontal line by typically not more than ± 4 years, which - if confirmed - would strongly speak in favor of a noise-perturbed, but nevertheless clocked process. The corresponding residuals for Usoskin's original minima are shown as the uppermost green line with open circles (which is - for better visibility - vertically shifted). Between 1140 and 1640, it exhibits already a long horizontal segment, pointing again to phase stability in this interval. Not surprisingly, however, it shows two steep downward-directed phase-jumps around 1650 and 1840, where the two additional minima of Usoskin et al. (2021) are intervening, as discussed earlier. Another remarkable feature is the downward-pointing "nose" centered around 1090 resulting from the two additional minima in the early segment, combined with two missing minima in the later segment of the 1040 – 1140 interval.

The light blue curve represents the residuals (again vertically shifted) after having contracted the two minima at 1839 and 1846 into one at 1843. As a consequence, the downward-directed phase jump disappears here. The next correction, i.e., the cancellation of the minimum at 1650, leads to the yellow curve, which is already dominated by a long horizontal segment between 1140 and 1890.

We now turn to the most problematic "nose" between 1040 and 1140. All three black curves in Figure 4 rely on the insertion of two additional minima at 1115 and 1133 in the late segment, as was specified by the dashed violet arrows in Figure 3. They differ, however, by the specific combination of the two canceled minima in the early segment, as shown in the three panels of Figure 3. Full, dashed, and dotted black lines in Figure 4 correspond to

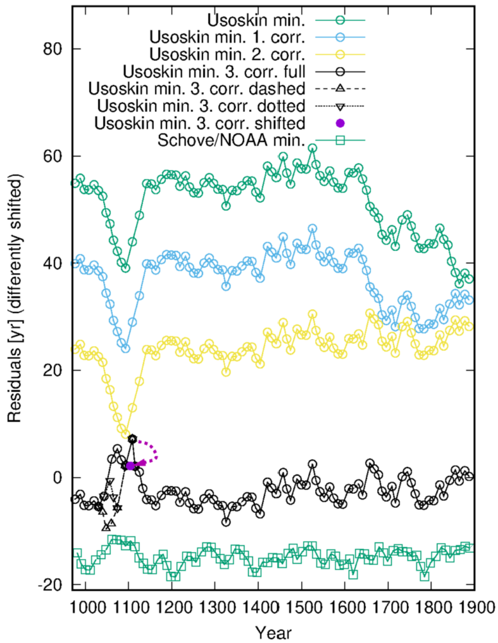

Figure 4 O-C plot of various data sets of cycle minima. For the sake of better visibility, the residuals (which all refer to a linear trend with the 11.07-year period) are differently shifted on the ordinate axis. The *light-blue, yellow*, and *black curves* correspond to the different corrections in the various panels of Figures 2 and 3. The *single violet full circle* corresponds to a possible shift of the 1109-year minimum as proposed in Figure 3.

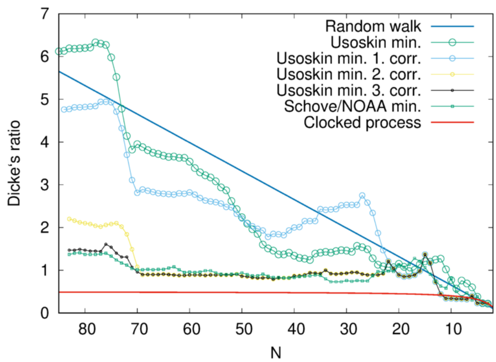

Figure 5 Dicke's ratio for the residuals shown in Figure 4, with corresponding colors.

the different types of crosses in Figure 3. In either case, the previous downward-directed "nose" morphs into a (mainly) upward-directed one, which, however, is significantly less pronounced. Still, there remains one rather dominant peak at 1109. If we were to shift the corresponding minimum to the more plausible year 1104 (as shown by the bent dotted violet line in Figure 3), we would end up here at the violet full circle in Figure 4. Finally, with those corrections in the three intervals, we arrive at the rather horizontal black lines in Figure 4, which are wiggling around a horizontal by not more than ±5 years, quite similarly to the Schove/NOAA data.

In Figure 5, we show now Dicke's ratio corresponding to all the lines depicted in Figure 4. This quantity is defined as the ratio $\sum_i^N r_i^2 / \sum_i^N (r_i - r_{i-1})^2$ between the mean square of the residuals r_i to the mean square of the differences $r_i - r_{i-1}$ between two consecutive residuals (Dicke, 1978). Here N denotes the number of residuals that are actually taken into account. For a random walk process, Dicke's ratio behaves as $(N+1)(N^2-1)/(3(5N^2+6N-$

3)) (dark blue line in Figure 5) with its asymptotic limit $N/15$, while the corresponding dependence for a clocked process reads $(N^2 - 1)/(2(N^2 + 2N + 3))$ (red line), with its asymptotic limit 1/2. Note that in Figure 5 - in contrast to the residuals in Figure 4 - the period is not fixed to 11.07 years but is separately computed for each number N of data points taken into account. The lowermost green curve shows - again for the Schove/NOAA data - a close proximity to the curve for a clocked process with its asymptotic limit 1/2. By contrast, Dicke's ratio for Usoskin's original data (upper green curve) wiggles around the dark blue curve for a random walk process and agrees with the observation by Weisshaar, Cameron, and Schüssler (2023) (who used, though, the slightly different ratio of variances as derived by Gough 1981). The light blue curve appears after the first correction around 1840, and the yellow curve after the second correction around 1650. Hereby, we come already pretty close to the theoretical curve for a clocked process (red). The additional corrections between 1040 and 1140 (only shown for the full black curve in Figure 4) result then in the black curve that is very close to the one for the Schove/NOAA data.

It is remarkable that the drastic difference between an apparently random-walk-like curve such as the light blue one and an apparently clocked-process-like curve, such as the yellow one stems only from one single additional intervening minimum at 1650. If we assume - for the sake of argument - that the additional minimum at 1650 is indeed real, it would just correspond to one single phase jump embedded into an otherwise nicely clocked process, just as discussed recently (referring to other data sets) for two different phase-jump candidates at 1565 and 1795 (Stefani et al., 2020b). Showing a strong similarity to a random walk process, the shape of Dicke's ratio would then be completely misleading in this respect. In Figure 7 (Appendix), we also evidence a strong dependence of the shape of Dicke's ratio on the very position of such an intervening phase jump. It remains to be seen whether an appropriately constructed statistical measure could be found to reliably distinguish between random walk and clocked processes also in case of intervening phase jumps. For the time being, we advice to have always a complementary glance on the O-C diagram (such as Figure 4), which, in some sense, is an even more telling device than Dicke's ratio (or Gough's ratio, for that matter, which we show in the complementary Figure 8 (Appendix)).

Apart from that problem, we also observe that even for the Schove/NOAA and for the "optimally corrected" data of Usoskin, Dicke's ratio does not perfectly approach the asymptotic limit 1/2. At this point, we reiterate a pertinent argument discussed already in Figure 2 of Stefani, Giesecke, and Weier (2019) that a significant share of the variance of the residuals is contained in a long-term cycle of the Suess-de Vries type. This is again illustrated in Figure 6a, showing the residuals of the Schove/NOAA data this time for the enlarged interval from 980 to 2009, together with an optimal sinusoidal fit whose period turns out to be 203 years. It is evident that this Suess-de Vries type cycle entails quite a lot of the variance of the data. As a side remark: this outcome speaks much in favor of the quality of Schove's data who had - in the construction of his series - never "put in" any long-term periodicity of this kind (although he had recognized it well in hindsight, see p. 25 of Schove, 1983). When subtracting the fitted 203-year cycle from the original data, the remaining residuals produce a Dicke ratio, as shown in Figure 6b with the lower green curve (with triangles), which now much better approaches the asymptotic value of 1/2.

4. Conclusions

In this paper, we have reanalyzed the series of annual (pseudo) sunspot numbers from Usoskin et al. (2021) with particular view on a possible phase stability of the minima and maxima of the solar cycle.

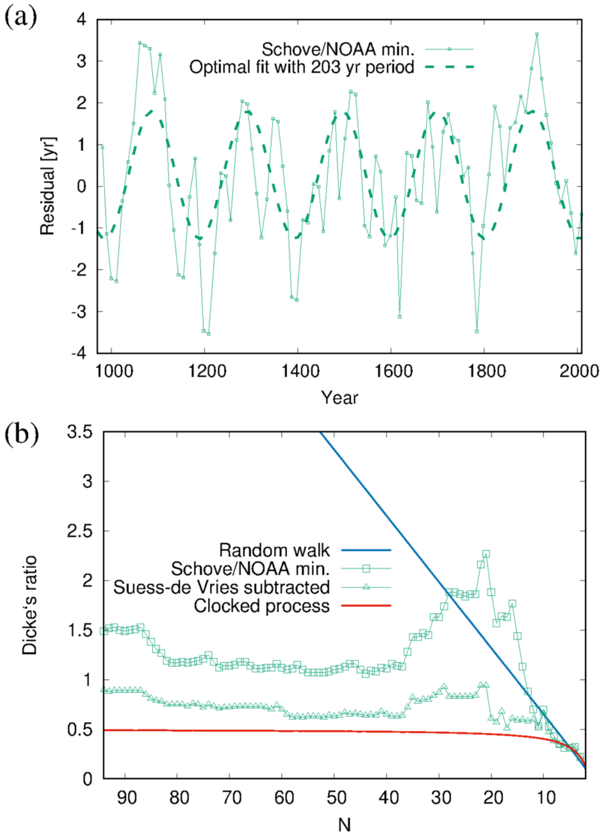

Figure 6 Illustration of the influence of the Suess-de Vries cycle on Dicke's ratio. (a) Residuals for the minima of the combined Schove/NOAA data for the extended interval until 2009. The *dashed thick line* represents an optimal fit of the residuals with a period of 203 years. (b) Dicke's ratio for the residuals of the data in (a) and for the corresponding data with the Suess-de Vries trend being subtracted beforehand. Evidently, after subtraction of the Suess-de Vries trend, the approachment of the curve towards the asymptotic limit 0.5 (for clocking) becomes significantly closer. Note, in particular, that the strong "overshooting" of the original Schove/NOAA curve for low N is widely suppressed by this subtraction.

The corresponding sequence of extrema was compared with another sequence comprising Schove's data until 1609 and the standard Schwabe cycles after that year. We have basically confirmed the outcome of Weisshaar, Cameron, and Schüssler (2023) by showing that the curve of Dicke's ratio for the original sequence of Usoskin's minima looks formally similar to that of a classical random walk process. Yet, we have also shown that this series comprises a very phase-stable segment interval between 1140 and 1640, with a one-to-one match of the corresponding extrema with those of the Schove/NOAA series. Given that there is only one possibility to get such a one-to-one match, in contrast to quite a number of possibilities to infer less or more extrema from the original ^{14}C data, this is already a remarkable result that also reassures the plausibility of Schove's cycle reconstruction (which is by some "regarded as archaic" (Usoskin, 2017)).

A first correction of Usoskin's series in the form of a contraction of two minima around 1840 into one seems highly plausible given the low-quality flag of the former of the two minima and the high observational validity of only one minimum in this time span.

We have tried a second correction in the form of a cancellation of one minimum at 1646. Here, amidst the Maunder minimum, the quality flags of all of Usoskin's minima are typically quite low. Admittedly, during this time, the observational validity of the standard Schwabe cycle is also not very high, so the justification for this cancellation remains doubtful. If we accept it for the moment (also considering that two successive short cycles are not very likely in this particular time of a very *weak* solar dynamo), we end up with a phase-stable time interval between 1140 and 1890, whose Dicke's ratio approaches closely the curve for a clocked process. But even if the additional minimum at 1646 turned out to be real, it would just correspond to one single phase jump, i.e., a short loss of synchronization, embedded into a long period that is otherwise phase stable. This property is best observed in the O-C diagram, while the curve of Dicke's ratio makes the data look like a random walk process.

The most ambiguous time interval is that between 1040 and 1140 (basically the Oort minimum), where nearly all quality flags of Usoskin's data are low. The O-C diagram exhibits here a pronounced downward-pointing "nose", stemming from two very long cycles in the later segment and some correspondingly short cycles in the earlier segment of this time interval. With two plausible insertions of minima in the later segment, and two compensating contractions/cancellations of minima in the earlier segment, we reach a reasonable one-to-one match with the minima of Schove again. The resulting O-C diagram is significantly smoothed and now shows a pretty horizontal line between 970 and 1890, with not much more wiggling (approximately ± 5 years) than in the case of the Schove/NOAA data. In our view, this finding strongly reinforces the validity of Schove's data and impugns Nataf's criticism of them as being simply construed by the "nine-per-century" rule.

Having been focused on a minimal number of corrections pointing (somewhat biasedly) *towards* a clocked process, we admit that the high ambiguity of Usoskins's extrema data (with 29 of them having a quality flag $q = 0$) also entails the possibility that even *more* phase jumps might exist. Obviously, with an increasing number of such events the entire notion of phase stability would become more and more problematic.

At any rate, we conclude that, before entering into a statistical analysis of the clocked - or non-clocked - character of the solar dynamo, the underlying data should be carefully scrutinized. The data set of cycle extrema as produced by Usoskin et al. (2021) entails quite a couple of intervals with low-quality flags where the specific extreme should be taken with a grain of salt. While this was clearly expressed in Usoskin et al. (2021), a too uncritical adoption of the data as by Weisshaar, Cameron, and Schüssler (2023) and Biswas et al. (2023) might lead to wrong conclusions. In this sense, their argument for a non-clocked process appears premature since its allegedly high significance depends crucially on the selection of the specific set of extrema according to Usoskin et al. (2021). While we still refrain from claiming perfect evidence *for* solar cycle synchronization, we argue that the work of Weisshaar, Cameron, and Schüssler (2023) does neither represent any conclusive evidence *for its absence*.

Appendix

In this appendix, we first illustrate the influence of an intervening additional minimum - embedded into an otherwise clocked process - on the shape of the curves of Dicke's ratio. For that purpose, we utilize the Schove/NOAA minima data, this time extended until 2009.

Figure 7 shows Dicke's ratio for this data set and for 6 further data, where phase jumps are artificially inserted at some appropriate positions close to the years 1000, 1200, 1400, 1600, 1800, and 2000. Obviously, the similarity of Dicke's ratio to that of a random walk process becomes most pronounced for phase jumps inserted in the center of the time interval.

Second, in Figure 8, we add - complementary to Dicke's ratio shown in Figure 5 - Gough's ratio between the variances of phase deviations and cycle periods, as used by Weisshaar, Cameron, and Schüssler (2023). Here we focus exclusively on the (corrected) original method of Gough for which the ratio for a random walk process reads $N(N+2)/(12(N+$

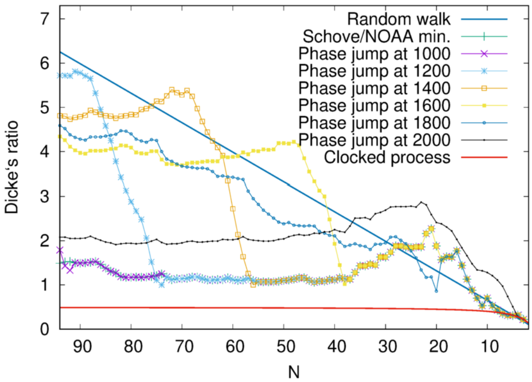

Figure 7 Dicke's ratio in dependence of the position of hypothetical phase jumps, based on the Schove/NOAA minimum data between 970 and 2009. Phase jumps are artificially inserted at appropriate positions close to the years 1000, 1200, 1400, 1600, 1800, and 2000.

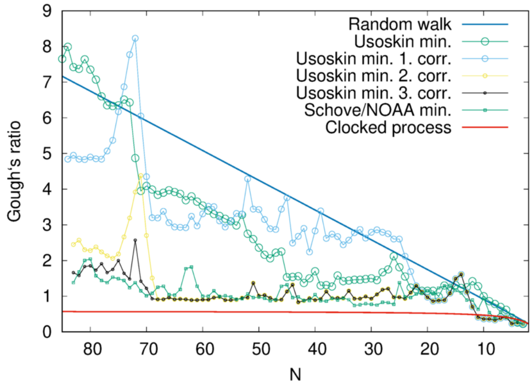

Figure 8 Gough's ratio for the residuals shown in Figure 4, with corresponding colors.

1)) (with the large-N-limit $N/12$), while the corresponding ratio for a clocked process reads $N(7N-2)/(12(N+1)^2)$ (with the limit $7/12$). While we prefer our traditional presentation in dependence on the number N of considered data-points over that of Weisshaar, Cameron, and Schüssler (2023), who had computed averages over contiguous segments with length N/q (q being divisors of N), for the full number $N=84$, we confirm the value 7.6 as found by those authors. Apart from that, we see that Gough's ratio for the different datasets and corrections behaves quite similar to (though a bit more spiky than) Dicke's ratio shown in Figure 5.

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Declarations

Competing interests The authors declare no competing interests.

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