A&A 557, A83 (2013)
DOI: 10.1051/0004-6361/201321713

Astronomy & Astrophysics

No evidence for planetary influence on solar activity

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Received 16 April 2013 / Accepted 24 July 2013

ABSTRACT

Context. Recently, Abreu et al. (2012, A&A. 548, A88) proposed a long-term modulation of solar activity through tidal effects exerted by the planets. This claim is based upon a comparison of (pseudo-)periodicities derived from records of cosmogenic isotopes with those arising from planetary torques on an ellipsoidally deformed Sun.

Aims. We examined the statistical significance of the reported similarity of the periods.

Methods. The tests carried out by Abreu et al. were repeated with artificial records of solar activity in the form of white or red noise. The tests were corrected for errors in the noise definition as well as in the apodisation and filtering of the random series.

Results. The corrected tests provide probabilities for chance coincidence that are higher than those claimed by Abreu et al. by about 3 and 8 orders of magnitude for white and red noise, respectively. For an unbiased choice of the width of the frequency bins used for the test (a constant multiple of the frequency resolution) the probabilities increase by another two orders of magnitude to 7.5% for red noise and 22% for white noise.

Conclusions. The apparent agreement between the periodicities in records of cosmogenic isotopes as proxies for solar activity and planetary torques is statistically insignificant. There is no evidence for a planetary influence on solar activity.

Key words. Sun: activity – methods: statistical – solar-terrestrial relations

1. Introduction

There is a long record of attempts to associate periodicities in the level of solar activity with the orbits of the planets. All of these eventually failed rigorous statistical tests (Charbonneau 2002), which is not surprising in view of the extreme tininess of the physical effects (e.g., Callebaut et al. 2012).

Recently, Abreu et al. (2012, hereafter A2012) made a new attempt in this direction by comparing periodicities detected in the records of cosmogenic isotopes ^{10}Be and ^{14}C (or quantities derived from them) as proxies for solar activity in the past 9400 years with those of the torque exerted on a thin shell of an ellipsoidally deformed Sun[1]. They found coincidences between selected periodicities in the planetary torque and the level of cosmogenic isotopes. After assessing the statistical significance under the assumption that the level of solar activity is a realisation of either white or red noise, they interpret their result as evidence for a planetary influence on long-term variations of the activity (in their words:"... highly statistically significant evidence for a causal relationship...").

Here we show that the statistical test presented by A2012 to demonstrate a causal link between the planetary orbits and the level of solar activity is conceptionally flawed and biased. Furthermore, their execution of the test contains severe technical errors. A corrected test reveals that the period coincidences reported by A2012 are statistically insignificant.

2. The procedure of Abreu et al.

A2012 chose 5 bands in the period range between 40 yr and 600 yr based on Fourier transforms of three records related to cosmogenic isotopes (^{10}Be, ^{14}C, and solar modulation potential ϕ, which are regarded as proxies of solar activity) and of the calculated time evolution of the planetary torque. By construction, each of these 5 bands contains both a spectral peak of the planetary torque series and of the cosmogenic records. The details of their procedure involving 7000-yr subsets of the data are described in Appendix A of A2012.

To determine if the similarity between the planetary torques and cosmogenic records could be due to chance, A2012 generated random ϕ records consisting of (what they considered to be) white or red noise and determined the probability that at least one of the 20 strongest peaks of the corresponding Fourier spectra falls in each of their spectral windows. They find very low probabilities, which they interpret as evidence for a planetary influence on solar activity.

3. Errors in the statistical test

There are four distinct errors in the analysis of statistical significance presented in A2012.

3.1. Conceptual error

In their approach, the authors of A2012 in effect test the following null hypothesis: "the occurrence of at least one of the 20 strongest peaks in the preselected spectral windows is consistent with white or red noise". If this null hypothesis could be rejected at a high significance level, it would only imply that white or red noise can probably be ruled out as a model for the record

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[1] The origin of such a localised deformation of the solar mass distribution is left obscure by the authors. They refer to results from helioseismology indicating a prolate tachocline, but the latter is a feature of differential rotation, which could at most slightly modify the anyway minuscule rotational deformation of the solar equipotential surfaces.

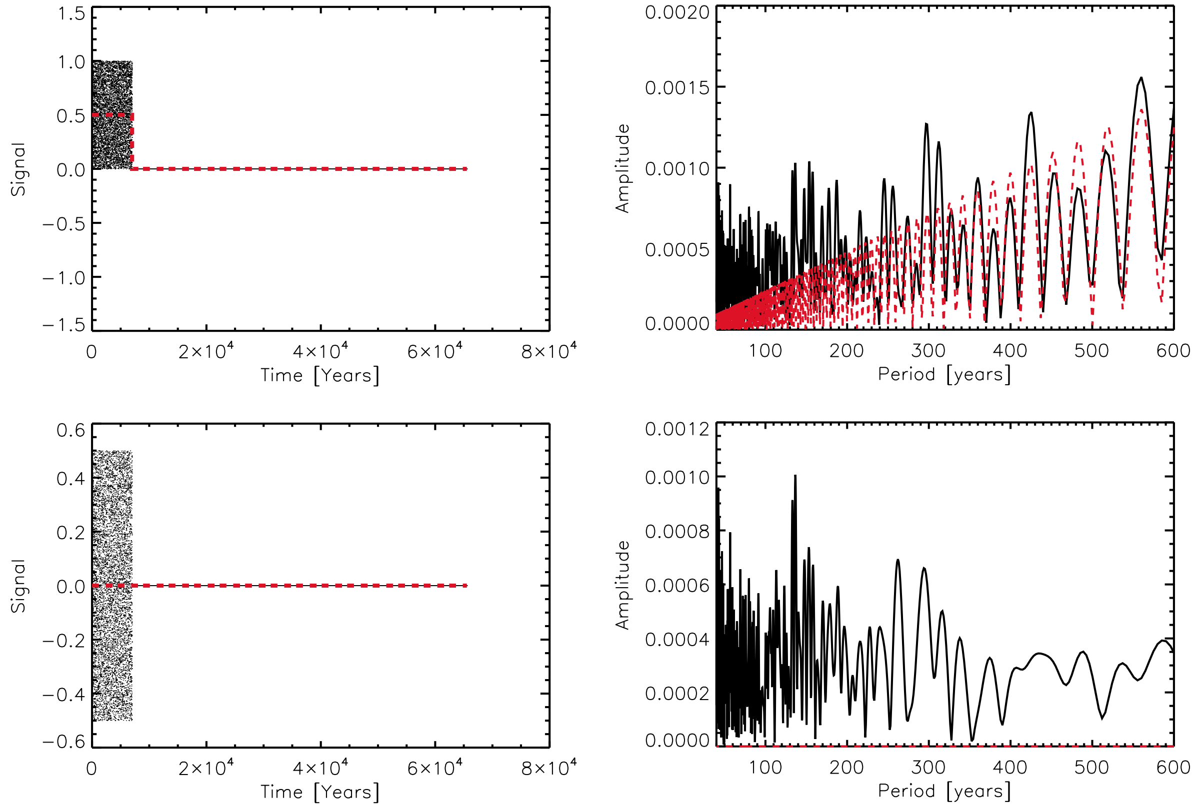

Fig. 1. "White noise" with zero padding as defined by A2012 (*upper row*) and properly constructed (*lower row*). The *left panels* show the time series while the *right panels* give the corresponding Fourier spectra. Red dashed lines indicate the systematic component of the signal and its spectrum.

of cosmogenic isotopes (as a proxy for solar activity) in the spectral range considered. This would not allow to draw any conclusion about a causal relation between planetary torque and solar activity. Such a relation could only be supported if virtually *all* possible statistical models for the solar activity record that do not have distinct periodicities in the given spectral range (e.g., other kinds of noise, nonlinear models, deterministic chaos) could be ruled out in the same way. By way of contrast, the failure of the test (inability to reject the null hypothesis) in only one of these cases is sufficient to show that the spectral coincidences do not support the presumed causal relationship. Therefore, the test of A2012 only leads to a clear conclusion if it fails.

In the subsequent subsections we repeat the test of A2012 and consider whether the spectrum with periods between 40 and 600 years generated from white or red noise is consistent with the observations. Both kinds of noise might not be particularly sensible physical models for solar activity (or, for that matter, for planetary effects since the test is symmetric), even over the restricted range of periods considered, but the aim here is to follow the analysis in A2012 and see if either of these models can be rejected. Our results show that the test as defined by A2012 indeed fails, i.e., that the period coincidences in the solar and planetary records are statistically consistent with both white and red noise. The contrasting result of A2012 follows from three errors in their definition and execution of the test.

3.2. Error in creating realisations of white and red noise

The random series considered by A2012 to be white noise consist of independent, uniformly distributed, random numbers between 0 and 1. Consequently, the expectation value differs from zero, in contrast to the definition of white noise. This has serious consequences for the Fourier spectra since the authors zero-padded the 7000-year time series to a length of 65 536 years and neither detrended nor apodized them (Beer, priv. comm.). As a result, a step function was introduced into the randomly generated time series. As is well known, this leads to spurious features in the spectrum, which invalidates the determination of the coincidence probability. This error carries over to the test with red noise, which was determined by A2012 as the time integral of their ill-defined series of white noise: since the numbers for the latter are non-negative, the resulting "red noise" series are monotonically increasing, followed by a big drop after zero-padding[2]. Examples of such time series and their Fourier transforms are shown in Fig. 1 (for "white noise") and Fig. 2 (for "red noise") along with padded time series of proper white and red noise. The figures demonstrate that the spectra as considered by A2012 are dominated by the spurious systematic components (indicated by the dashed lines) due to the jumps in the time series.

We quantitatively evaluated the effect of these errors on the statistical analysis by repeating the tests in the same manner as A2012, but with 100 000 time series each of proper white noise (uniformly distributed between −0.5 and +0.5) and proper red noise (determined by integration of series of proper white noise). The resulting probabilities for one of the top-twenty spectral peaks occuring in the windows selected by A2012 are shown in Table 1 (first two rows of the "Corrections") in comparison to the results given by A2012: the chance probabilities for coincidences in all spectral windows increase by about a

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[2] In the case that the already zero-padded white-noise signal is integrated, the drop occurs at the end of the time series segment, leading essentially to the same consequences.

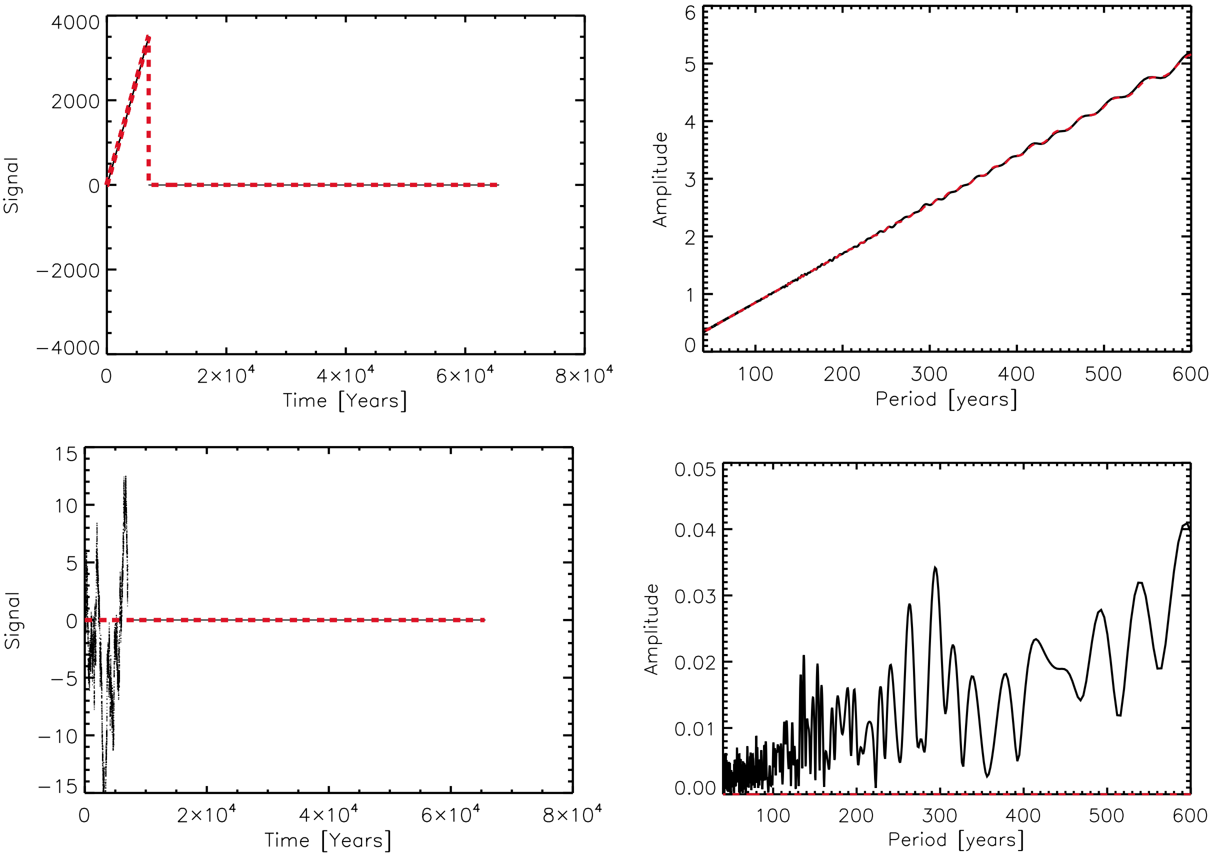

Fig. 2. Similar to Fig. 1, but for red noise.

Table 1. Probabilities for one of the top-twenty peaks falling in spectral windows (cf. Table 2).

Noise	Source	I	II	III	IV	V	all
"white"	Abreu et al. (2012)	0.143	0.104	0.168	0.189	0.0011	5.04×10^{-7}
"red"	Abreu et al. (2012)	2×10^{-6}	0.001	0.454	0.547	0.091	4.61×10^{-11}
	Corrections						
white	noise definition	0.46	0.29	0.22	0.09	0.04	1×10^{-4}
red	noise definition	0.02	0.06	0.31	0.34	0.24	7×10^{-5}
white	apodisation/filtering	0.59	0.40	0.32	0.13	0.06	5.2×10^{-4}
red	apodisation/filtering	0.46	0.45	0.52	0.24	0.11	2.5×10^{-3}
white	window bias	0.59	0.63	0.62	0.60	0.61	7.5×10^{-2}
red	window bias	0.46	0.68	0.74	0.92	0.94	2.2×10^{-1}

factor 200 for white noise and by more than a factor 10^6 for red noise, both reaching values around 10^{-4}.

3.3. Error in treating the randomly generated data differently from the observed data

A second error in the statistical test of A2012 is that they do not treat the random series in the same way as they treated the proxies for solar activity. As mentioned above, the noise series were neither apodized nor detrended, in contrast to the treatment of the observational data. Moreover, the ϕ data were filtered by applying a 22-year running mean (Steinhilber et al. 2012), which was not done in the case of the random series. Repeating the test by first applying a 22-year running average, then detrending and apodizing each realisation of proper white and red noise, respectively, we found that the probability of a match in all bands chosen in A2012 was increased by additional factors ~5 for white noise and ~36 for red noise, both now reaching values of the order of 10^{-3} (see Table 1, third and fourth row of the "Corrections"). These values are higher by about 3 order of magnitude for white noise and by about 8 orders of magnitude for red noise than those given by A2012.

3.4. Error introduced by window selection

After correcting the technical errors, the probabilities of a randomly chosen realisation matching the data, using the test of A2012, are 5×10^{-4} for white noise and 2.5×10^{-3} for red noise. These probabilities might still be considered to be sufficiently low to reject the null hypothesis given in Sect. 3.1.

Table 2. Properties of the spectral windows used by A2012.

Window [yr]	w [yr]^a	$\Delta P[yr]^b$	$w/\Delta P$
I: 85−89	4	1.08	3.70
II: 103−106	3	1.56	1.92
III: 146−151	5	3.15	1.59
IV: 206-210	4	6.18	0.65
V: 503−515	12	37.01	0.32

Notes. $^{(a)}$ Width of the spectral window; $^{(b)}$ period resolution (at central period of window).

However, the statistical test and, in particular, the size of the spectral windows used in A2012 were defined a posteriori on the basis of the data themselves. The windows were chosen so that spectral peaks from the observations (the cosmogenic isotope series) and from the model (the torque induced by the planets) fall within the windows. This manifestly biases the statistical test – a procedure that can easily produce seemingly significant results for fully random data (see below). An unbiased procedure would have been to first define a criterion for a satisfactory agreement of periods (evidently a constant multiple of the period resolution), then inspect the data for such coincidences, and then perform the test using the above criterion for the window size.

Table 2 shows the properties of the spectral windows selected by A2012. Note that the windows are nonuniform in terms of the period resolution of the Fourier spectra. In particular, the first window (85−89 yr) has a size of 3.7 times the period resolution, $\Delta P = P^2/T$ (P: period, $T = 7000$ yr: length of dataset), of 1.08 yr for that window, thus accomodating the clearly resolved disagreement between the periodicities detected for this period range in the different datasets. In contrast, the last window (503−515 yr) has a width of only 0.32 of the period resolution in the corresponding spectral range.

To estimate a lower bound for the effect of defining the test a posteriori on the basis of the data, we consider windows of uniform width (in terms of the period resolution). We choose the width as $3.7\Delta P$, corresponding to the period bin between 85 and 89 years defined by A2012. For this bin, the planetary forcing has a peak at 86 years and the solar activity has a peak at 88 years. Regarding the forcing peak as given, for "coincidence" we should allow the solar peak to fall in the interval 86 ± 2 years, i.e., in the range between 84−88 years. A2012 choose the interval 85−89 years, the average of the ranges assuming that either planetary forcing or solar activity is given. Consequently, using windows narrower than 3.7 times the period resolution would lead to the planetary forcing peak at 86 years and the solar activity peak at 88 years being noncoincident. Therefore, a window width of $3.7\Delta P$ is the minimum required for a test including all 5 period bins considered by A2012.

Using 100 000 realisations of white and red noise, respectively, we calculated the probabilities for coincidences of top-twenty spectral peaks in the windows centered on those of A2012, but with widths of $3.7\Delta P$. The resulting probabilities for coincidences in all windows are 7.5% for white noise and 22% for red noise (see Table 1, last two rows). These numbers show that the test has failed, i.e., the period coincidences between isotope data and planetary torque are statistically consisten with both white noise and red noise.

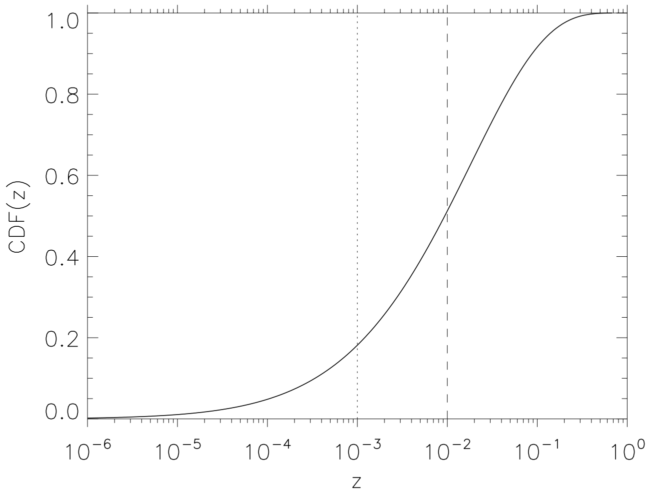

Fig. 3. Cumulative distribution function for the relative change of the chance probability (for tests with random time series) due to shrinking of the period windows. The vertical lines indicate apparent increases in the test significance by factors of 100 (dashed line) and 1000 (dotted line).

The strong bias that is introduced by tayloring the widths of the spectral windows on the basis of the data themselves can be illustrated and quantitatively analysed as follows. Assume a set of five periods (the "planetary" periods) and five windows in period space of width $w_m = k\Delta P$, the value of k being chosen according to a predefined criterion of satisfactory agreement of periods. Assume a second time series (the "solar" series) that happens to show at least one of its top-twenty spectral peaks in each of the windows. We can now carry out the test with noise series and determine the probability for chance coincidences of periods in the given windows. It is clear that we can make the coincidence of the periods appear more significant (i.e., obtain lower values for the chance coincidences in the random test) if we inspect the data and shrink the spectral windows such that they just cover the "planetary" peaks and the corresponding peaks of the "solar" time series. Assume that the "solar" time series is one realisation of a process with a random component and that w_m is sufficiently small so that the position of the "solar" peaks within the original windows for different realisations has a uniform distribution[3]. We can then easily determine the distribution of the resulting change of the chance probability obtained in a random test. For each realisation, the windows are shrunk according to the distance between the central ("planetary") and the respective "solar" peak (symmetric with respect to the central peak). The relative size change of each window is then uniformly distributed between 0 and 1, so that the relative change of the chance probability in a random test is given by the product of five random numbers from this distribution. The probability density function of this product, z, is given by $PDF(z) = (\ln z^4)/24$. The corresponding cumulative distribution function (CDF) is shown in Fig. 3. It demonstrates that in about 50% of the cases the shrinking of the windows (biasing of the test a posteriori) leads to an apparent increase of the significance for the random test by a factor >100 and in about 18% of the cases by a factor >1000. This fits well well the results shown in Table 1, which also show an apparent significance boost by a factor of about 100 when going from equal-sized windows to the hand-selected windows of A2012.

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[3] Actually, the same result is obtained also for a linear distribution in period.

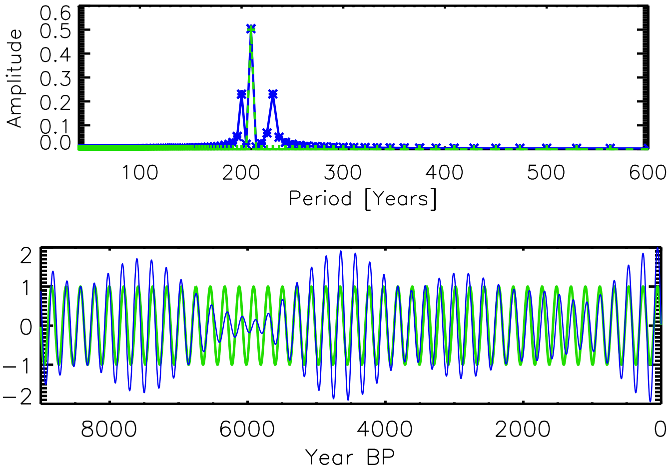

Fig. 4. Power spectra (*upper panel*) and time series (*lower panel*) of a synthetic planetary forcing signal assumed to consist of a single sinusoidal mode with a period of 209.3 years (green lines) and a synthetic solar activity signal which has two additional peaks at 199.3 and 229.3 years. In the time domain, the side bands can be seen to beat against the central peak. This similar to what A2012 interpret as phase-locking. Since it is merely the time-domain counterpart to the frequency-domain signal, it does not provide any evidence for a physical connection of the signals.

4. "Phase locking"

We have seen (cf. Table 2) that several of the period windows selected by A2012, including that between 206 and 210 years, are narrower than the resolution limit implied by 7000 years of data. In the time domain, the signal coming from these two peaks will not drift in phase throughout the temporal interval studied. In addition, the bandpass filter of 190−230 years used by A2012 is broad enough to contain side peaks with (resolvable) different frequencies and thus introduces beating. The beating is considerable for the solar activity signal, which has substantial power in the side bands, but neglible for the planetary forcing signal, which is almost monochromatic in the frequency subdomain of the filter (cf. Fig. 5 of A2012). Without the effect of the beating, the two signals would not drift in phase. Correspondingly, at times when the central peak and the side bands are in phase, the amplitude of the (filtered) solar activity signal is large and in phase with the planetary forcing signal. Conversely when the components of the solar activity signal are out of phase, the amplitude of the signal is low and the phase will be different from that of the planetary forcing (see Figs. 6 and 7 of A2012).

To illustrate the effect of beating on the relative phases, we consider an example for which the planetary forcing is a simple sinusoid with a period of 209.3 years, and the solar activity consists of the superposition of three sinusoids with periods of 199.3, 209.3, and 229.3 years and amplitudes of 0.5, 1., and 0.5, respectively. Figure 4 shows this signal in the spectral and time domains.

This demonstrates that the "phase locking" considered by A2012 as an independent piece of evidence for an effect of the planets on solar activity is merely a consequence of finding two peaks in a period band narrower than the resolution limit and beating against sidebands. Therefore the reported "phase locking" is simply the time-domain counterpart to the coincidence of the peaks in frequency space and does not add to the statistical significance of the results.

5. Concluding remarks

The statistical test proposed by Abreu et al. (2012), a comparison of the coincidences of spectral peaks from time series of planetary torques and cosmogenic isotopes (taken as a proxy for solar activity in the past) with red and white noise, is logically unable to substantiate a causal relation between solar activity and planetary orbits. Furthermore, the execution of the test contains severe technical errors in the generation and in the treatment of the random series. Correction of these errors and removal of the bias introduced by the tayloring of the spectral windows a posteriori leads to probabilities for period coincidences by chance of 22% for red noise and 7.5% for white noise. The coincidences reported in Abreu et al. (2012) are therefore consistent with both white and red noise.

Owing to our lack of understanding of the solar dynamo mechanism, red or white noise are only one of many possible representations of its variability in the period range between 40 and 600 years in the absence of external effects. This is why the test of A2012 is logically incapable of providing statistical evidence in favour of a planetary influence. Alternatively one could consider the probability that a planetary system selected randomly from the set of all possible solar systems would have periods matching those in the cosmogenic records. In the absence of a quantitative understanding of the statistical properties of the set of possible solar systems to draw from, the comparison could again, at best, rule out a particular model of the probability distribution of planetary systems. Here we have shown that the test in A2012 does not exclude that the peaks in the range from 40 to 600 years in the planetary forcing are drawn from a distribution of red or white noise.

We conclude that the data considered by A2012 do not provide statistically significant evidence for an effect of the planets on solar activity.

Acknowledgements. We are grateful to Aaron Birch for useful comments on an earlier version of the manuscript.

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