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Footnotes

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ORIGINAL ARTICLE

Solar 22 years cycle

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Abstract Seven observatories performed in 1968–2015 numerous daily measurements of general magnetic field of the Sun seen as a star (of a mean line-of-sight field component of the visible solar hemisphere). The new data 2013–2015 confirmed the recent prediction about saw-edged profile of the mean curve of the Hale's 22 years magnetic cycle and, thus, a hypothesis about its cosmological (partial) origin. This is supported by a special analysis of epochs of extrema of Wolf's sunspot number, demonstrating a remarkable stability, since Galileo's time, of the initial phase of the cycle, which can hardly be explained by dynamo theory exclusively.

Keywords Sun: photosphere: magnetic field · 22 years cycle

1 Introduction

The new characteristics of variability of the Sun, besides spots, is its general magnetic field (GMF), recorded by Zeeman effect of absorption spectral lines of the photosphere. For such measurements, *the Sun is observed as a star*: solar magnetograph registers a mean longitudinal field strength B of the total visible solar hemisphere (GMF is known elsewhere as the *solar mean magnetic field*, SMMF; for details see Severny 1969; Scherrer et al. 1977; Kotov 2015).

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In 1968–2015, these measurements were performed at the Crimean Astrophysical Observatory (CrAO; CrAOCriema.ru), Mount Wilson Observatory, J. Wilcox Solar Observatory (WSO, Stanford University; WSO.Stanford.edu), Sayan (Demidov et al. 2002), Sutherland (Birmingham University; Chaplin et al. 2003), National Solar Observatory (NSO; SOLIS.NSO.edu/vsm) and Kislovodsk (Pulkovo Observatory). Special procedures were employed at each site to determine an actual zero level of the instrument.

Individual GMF datasets were merged into a single 48-year *normalized* time series with the total number $N = 25648$ of daily B values, standard deviation $\langle S_0 \rangle = 0.61$ G and the mean $-0.013(4)$ G (standard error is given in brackets). To get this common dataset, the original B-values of each observatory,—and of each spectral line,—were reduced to the average rms-value $\langle S_0 \rangle$ (the mean of original rms-values S_0 of eight original datasets) by factors $k = \langle S_0 \rangle / S_0$. They are listed in the last column of Table 1, which gives parameters of *eight* individual datasets, because Crimean observers measured GMF in two iron lines; N gives an amount of daily B-values of each dataset, with Δ being a typical uncertainty of measurements (for details of data reduction procedure see Kotov 2006).

Positive B values correspond to nothern (N) polarity, zero phase—to 0 UT on 1 January, 1968, and the power spectra (PS'a) were computed by direct Fourier transform. We estimated confidence level (C.L.) of the prominent peaks by the Scargle's (1982) technique, and use sometimes the term *PS* instead of *periodogram*.

Here we analyse the GMF dataset extended by three years to 2015, and this extension serves as a basis for the present work (it builds on the recent result by Kotov 2015).

Analysis of the previous, 1968–2012, data has led to conclusion that 22-year magnetic, or Hale's, cycle has rather odd, saw-tooth, shape of the field variation, which

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Table 1 The GMF data 1968–2015

Observatory	Years	Line, nm	N	Δ, G	S_0, G	k
CrAO	1968–2015	Fe I λ525.02	3647	0.11	0.62	0.99
CrAO	2001–2015	Fe I λ524.71	1630	0.14	0.63	0.97
Mount Wilson	1970–1982	Fe I λ525.02	2457	0.07	0.67	0.91
Stanford	1975–2015	"	12141	0.05	0.39	1.59
Sayan	1982–2015	"	477	0.05	0.72	0.85
Sutherland	1992–2001	K I λ769.90	1988	0.01	0.43	1.42
NSO	2003–2015	Fe I λ630.15	3013	0.01	0.45	1.35
Kislovodsk	2014–2015	Fe I λ630.25	295	0.01	0.99	0.62
Total[a]	1968–2015	–	25648	–	0.61	–

[a]Normalized dataset.

seems hardly being explained by dynamo mechanism (Kotov 2015). Is this result supported by the latest GMF measurements? What explanation of additional *external* roots of the solar activity cycle could be proposed? We shall try to answer these questions, using longer GMF (or SMMF) time series, analysing time behaviour of sunspot number and extending interpretation.

2 Sunspot cycle

Analysis of extrema of the 11-year (Wolf) sunspot cycle suggests that the cycle "remembers" its initial phaee at least suince the times of Galileo. We try to show this cannot be explained in terms of local physics and notions of the past century about the cause of the cycle based exclusively on dynamo theory and the Babcock–Leighton model of the magnetic cycle (see also Dicke 1978).

To substantiate this statement, we analysed epochs of extrema of the Wolf sunspot number W from 1610 through 2015 (according to Allen 1973, and NGDC.NOAA.gov). The $+1$ or -1 ordinates were ascribed to times of Wolf maxima or minima, respectively, then the *periodogram* $F(\nu)$ of this time series was computed (ν is test frequency, changing within sufficiently wide range). The result is plotted in Fig. 1, where the unique and *unsplitted* peak corresponds to a period of 11.07(8) years. The latter, together with deep reasonings of Dicke (1978), demonstrates a cyclic behaviour of our star, ruled by enigmatic "clock" mechanism, hidden within the Sun (or outside?) and which forces it to "remember" an initial phase over centuries.

Then we prepared the list of 37 epochs of spot minima, determined with uncertainty ± 0.5 years, and constructed the phase diagram O–C ("observation minus calculation") for the trial period 11.00 years. This diagram is depicted in Fig. 2, where the phases φ of minima are shown by dots (for the phase interval 0–1, being repeated for intervals 1–2 and 2–3). The slope of the linear regression lines indicates that the true period is equal to 11.09(3) years. Similar diagram, obtained for 37 epochs of spot maxima (with

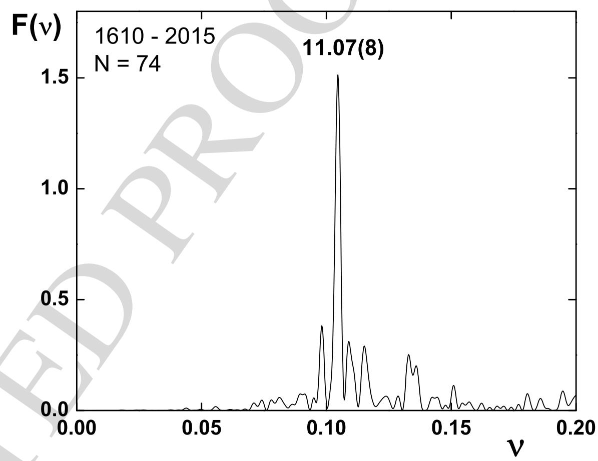

Fig. 1 Periodogram of epochs of Wolf extrema (1610–2015, the total amount of epochs $N = 74$). On *horizontal axis*—frequency ν in units 1/36.5256 μHz, on the *vertical* one—power $F(\nu)$ in arbitrary units, and the highest peak corresponds to period 11.07(8) years

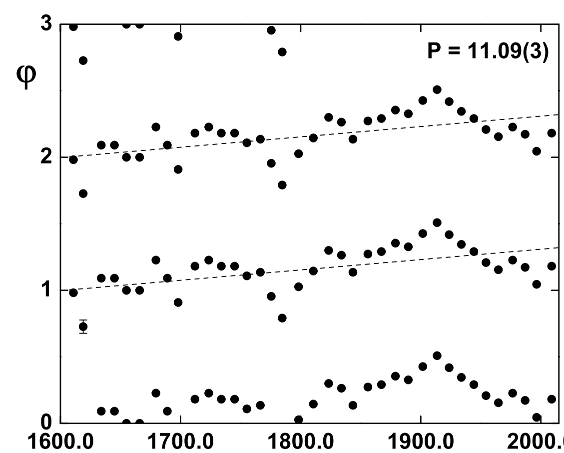

Fig. 2 Diagram O–C plotted for 37 epochs of sunspot minima (shown by *dots*, 1610–2015) with the folding period 11.00 years. *Horiziontal axis* gives years, the *vertical* one—phases φ of spot minima, the *error bar* shows a typical uncertainty in phase φ and the two *dashed sloping lines*, corresponding to linear regressions, give true period $P = 11.09(3)$ years (zero phase here corresponds to 1600.0)

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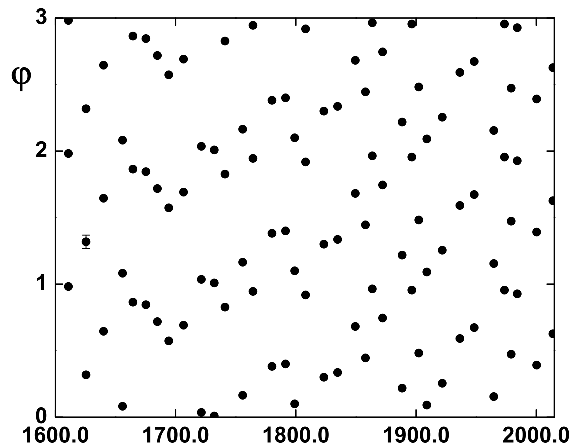

Fig. 3 Same as Fig. 2, for a "random" Sun with the dispersion limit $L = \pm 0.5$

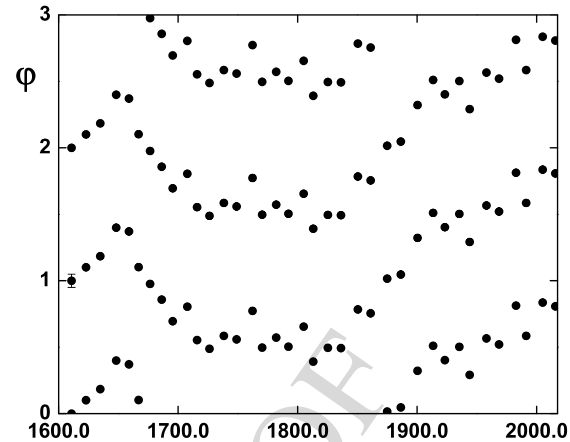

Fig. 4 Same as Fig. 3, for $L = \pm 0.3$

somewhat larger dispersion of phases φ), produced period 11.04(4) years.

For the best value of the Wolf period, as determined by O–C diagrams, we take a statistical average $P_W = 11.07(4)$ years, which agrees well with the value, following from the above periodogram, and with both Wolf's value 11.11 years and Allen's (1973) value 11.04 years. Thus, for the Hale's period we get:

$$P_H = 2P_W = 22.14(8) \text{ years.} \tag{1}$$

An observed length of the Wolf cycle during last 405 years has varied from 7.3 to 17.1 years. Therefore, to check strict validity of dynamo process, we simulated a "random" Sun, with chance fluctuations of minimum epochs. For this aim, the length of each successive 11-year cycle assumed to be variable (variations were modeled by random numbers, evenly distributed within relative limits ± 0.5). The O–C diagram, shown in Fig. 3 for new minimum epochs, shows that the Wolf cycle of such "randomly scattered" Sun fully disappeared: random phase deviations destroy coherency. (An actual cause is that deviations cannot be remembered by dynamo and convective motions themselves; the final result will be a random walk of Wolf extrema times, similar to that in Fig. 3.)

However, varying the random length of the Wolf cycle within phase dispersion limits $L = \pm 0.5$ seems to be too large, making phase coherency break down very quickly (dynamo could produce perhaps less variability, maintaining coherency for centuries). To check the sensitivity of the "random model" to L, we adopted the dispersion limit $L = \pm 0.3$ for minima epochs. The result is shown in Fig. 4, where, instead of the P_W periodicity (corresponding to the slope of linear regression lines in Fig. 2), one observes "waves"—apparently chaotic—of dots (phases φ), which evidently should destroy the Wolf cycle coherency and, thus, will result in a splitting and/or disappearance of the P_W peak in the corresponding periodogram (quite other situation is demonstrated by Figs. 1 and 2; comparing with the observations in Figure 2 might allow, in principle, to place meaningful limits on L that dynamo modelers would find useful). Therefore, a long time coherency of the Wolf cycle requires the limit L to be near zero, or even zero,—suggesting thus some external synchronization would be at work.

We recognize that some solar dynamos. in fact, vary in such a way, that they become capable to maintaim phase coherency for some time. A few authors, moreover, paid attention to nonlinear behaviour of the Wolf number curve, with alternation of even and odd cycles,—a demonstration of the well-known Gnevyshev and Ohl's (1948) rule,—see, e.g., Levy and Boyer (1982). To get the new periodic solution of differential equations, they tried to address problem to interference of photospheric fields with an additional quasi-uniform component of the mean field. Some other dynamo models can be also, apparently, consistent with that rule, because ideal solutions might have smooth variability. This does not mean of course that the models are incorrect, but one must stress all of them require several free, taken *a priori*, parameters to make models to be consistent with observations. Cit., for instance, Ruzmaikin (1985): "In the even cycle it [an additional quasi-uniform component of the mean field,—VK, FS] is added to the oscillating field, in the odd cycle it is subtracted. The origin of this component is still enigma.". One must conclude therefore that cyclic activity of our Sun might be directed also by unknown, additional to dynamo, mechanism, maintaining initial phase of the Wolf cycle over centuries (see again Dicke 1978), with alternation of even and odd cycles.

3 GMF, 1968–2015

Let us consider the *normalized* time series 1968–2015 of the GMF, averaged within 1-year intervals (this procedure made data free from influence of solar rotation).

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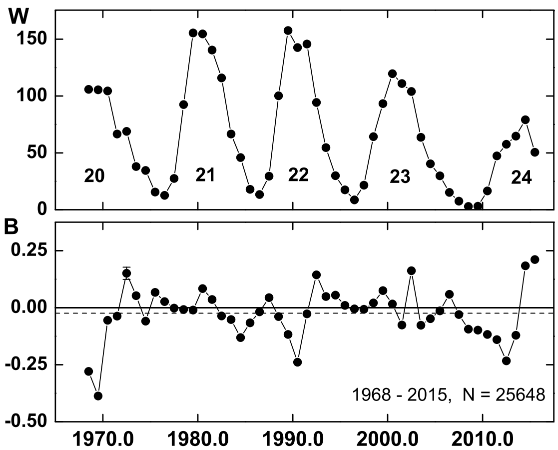

Fig. 5 Annual means of the Wolf number W (*top*) and the GMF strength B (*bottom*) plotted over last 48 years. The *error bar* (*bottom*) is shown on one representative point (for 1972; the actual standard errors are 2–3 times larger for 1968–1970 data, with small annual amounts of measurements), and the *dashed horizontal line* corresponds to the mean GMF level $-0.024(17)$ G. *Horizontal axis* gives years, and the Wolf cycle numbers are indicated under the top curve

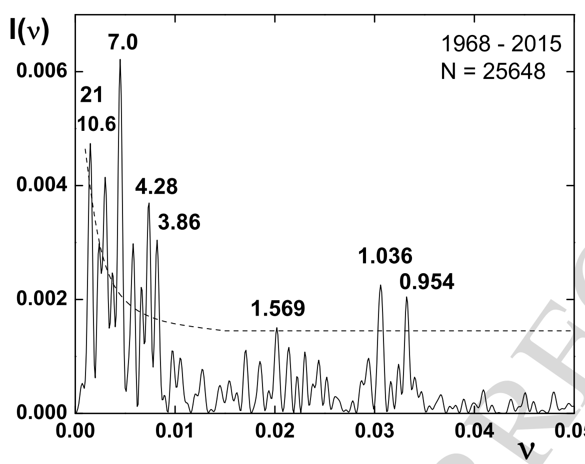

Fig. 6 PS of the GMF data 1968–2015 (the number of daily B values $N = 25648$). On *horizontal axis*—frequency ν in μHz, on the *vertical* one—power $I(\nu)$ in arbitrary units, and the *dotted line* shows 3σ C.L.; the primary peaks are marked by numbers (periods in years)

The prediction (made in 2013; see Kotov 2015) of an abrupt GMF rise from S- to N-polarity for 2014 is now well confirmed by Fig. 5 where time variations of the yearly-means of the Wolf numbers W (top) and GMF strength (bottom) are shown for the past 48 years. Notice also that the overall mean value of GMF, determined by averaging of the annual means and shown by horizontal dotted line, is almost zero.

The PS of normalized *daily* GMF data 1968–2015 is plotted in Fig. 6, where the dashed line shows a 3σ C.L. (for frequencies $\nu \lesssim 0.015$ μHz, this level grows approximately like that for red noise, $I(\nu) \sim \nu^{-1}$; for details and interpretation of high-frequency periodicities see Kotov 2006, 2013).

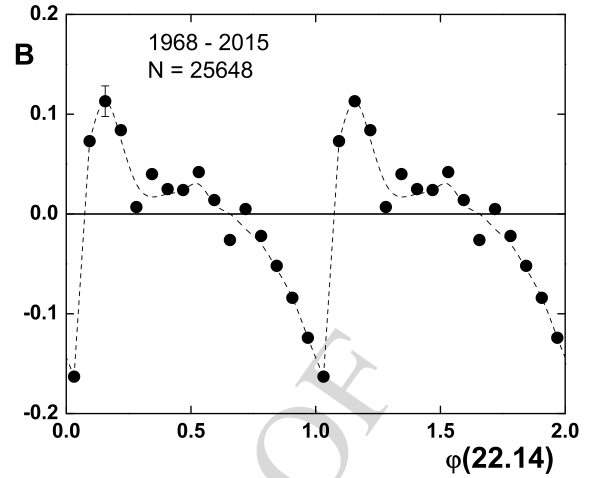

Fig. 7 The GMF mean curve plotted with the folding period 22.14 years (1968–2015, $N = 25648$). On the *vertical axis*—strength B in G, the *horizontal axis* gives phase φ, and the *error bar*, shown on one representative point, is a typical standard error for each of 16 blocks of data. The *dashed line* approximates the mean curve

Further we discuss three lowest-frequency peaks only. One of them, with a period of $P_C = 21.1(2.3)$ years, corresponds, within error limits, to the Hale's period $P_H = 22.14(8)$ years. The other two prominent peaks, with periods 10.6(6) years and $P_7 = 7.04(26)$ years, may be treated as 1:2 and 1:3 overtones of the primary P_C peak; their appearance is naturally expected owing to strong non-sinusoidal character of the mean Hale's profile, see below (other two noticeable peaks, with periods ≈ 3.9 and 4.3 years, might be treated as overtones of the P_C peak too, or as products of noise). A proximity of P_7 to 3d harmonic of P_H is tied explicitly to strong GMF minima, observed in 1969, 1990 and 2012, see Fig. 5, bottom.

4 The 22 years mean curve

The mean curve, obtained with the folding Hale's period and shown in Fig. 7, reveals a saw-tooth-like profile with the negative extremum at the phase $\varphi \approx 0.03$. The odd appearance of the curve, with a strong jump after that phase, stimulated discussion about a *cosmic* origin of the period (see Sects. 5 and 6 and Sanchez et al. 2011; Kotov 2015). Note that the main feature of the curve—an abrupt change in phase—is readily observed in the original time series, see Fig. 5 and e-sites, mentioned in Sect. 1.

The curve confirms the Gnevyshev and Ohl's (1948) rule, but for GMF, not for spots: the Hale's cycle consists of two 11-year cycles, starting with that of even number, which has small W amplitude. Note also that the GMF jumps, or "breaks", take place near sunspot maxima of even Wolf cycles. It is remarkable that the 22 years curve apparently ignores the presence of a Wolf 11-year cycle of sunspots. In-

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deed, according to dynamo mechanism and the Babcock–Leighton model, time behaviour of magnetic field—during a given Wolf cycle, after polar reversal,—should be mirror reflection of a previous one.

5 Why cosmic influence?

According to the data prior to 2013 (Kotov 2015), and if a suggestion about a "cosmic" signature of 22-year periodicity were correct, one would see *(a)* a GMF negative extremum in 2012–2013, *(b)* a prevalence of N-field in approximately 2014–2015, and *(c)* an abrupt rise from S- to N-polarity (predominant) in 2013–2014. It is exactly observed in reality, see Fig. 5,—supporting thus our earlier conclusion about a plausible cosmic (at least partial, concerning phase coherency) origin of the Hale's period. The latter seems to be *the most fundamental* for solar magnetic activity, and one may look for other mechanism, additional to dynamo, of the Hale's cycle emergence in the Sun. We note that the necessity for some trigger that maintains the initial phase of the cycle, appears to be the key result of this research. But whether the synchronizing agent could be of something inner or something cosmic origin to the Sun is of course arguable. As the reviewer rightly pointed out, it could be just a matter of having dynamo with proper dispersion limit L (see Sect. 2); or "perhaps rather than an external trigger, there could be an interaction with an internal relic field that explain the phase or the presence of long-term regularities in the sector magnetic pattern". So far one may advance some hypotheses only.

A conception about a possible substantial role of Cosmos is suggested by holographic relations (Sanchez et al. 2011). But observations of 22(11) years periodicity in other astronomical objects may possibly serve as another signs too. Because it is reasonable to expect that solar-like stars would have cycle periods more or less like that of the Sun. And there are already some examples: 7 to 20 years periodicities of chromospheric activity of a number of solar type stars were already discovered during last five decades (Baliunas et al. 1995; Bruevich et al. 2016).

Another interesting example is the 11–12 years period of luminosity variations,—of peculiar non-sinusoidal profile and with highly significant amplitude,—of the blazar OJ 287. For an explanation, Valtonen et al. (2010) proposed a binary black hole model: the mass of a primary component is equal to $\approx 1.8 \times 10^{10} M_{\odot}$, and it is accompanied by a secondary of 130 times less mass (notations are usual). The idea, having plausible physical mechanism, does not exclude a possibility of cosmic (hypothetical) origin, like that of the Sun. (Astronomical objects, however, have wide distribution of periods, so that closeness of OJ 287 period to the solar Wolf's one might be just a chance coincidence; this requires special investigation.) And there are a few other arguments lying in the base of our hypothesis.

At the present time, the solar 22(11) years cycle is thought to be well understood in terms of hydromagnetic dynamo, and we shall not discuss here many popular dynamo explanations (see, e.g., Ruzmaikin 1985; Obridko 2008, and results of the solar cycle modeling efforts, undertaken during last four decades by many authors). However, some properties of the magnetic Sun contradict this mechanism, which does not expose, perhaps, true roots of the phenomenon and cannot be considered hence as a final solution of the problem.

Serious question concerns the solar sector magnetic pattern ignoring 11-year cycle, differential rotation and equator of the Sun (Svalgaard and Wilcox 1975; Kotov 2010). Indeed, it seems hard to understand,—in frames of dynamo mechanism and the subsequent *polar reversals* of global field, as observed each 11-year cycle,—a remarkable long-time stability of magnetic sectors observed over a few 11-year cycles, with north–south orientation of sector borders, neglecting equator,—i.e. with sectors of identical polarity on both sides from it. These facts forced Wilcox (1971) to suppose that there is an *additional* type of solar magnetism, which properties substantially differ from those dictated by dynamo and Babcock–Leighton model of the cycle. Calling second system of fields by *solar sector magnetism*, Wilcox emphasized that classic model of the cycle is not completed.

Notice also that one of the primary cycles of the GMF variations (apart changes caused by solar rotation) is the Hale's cycle P_H, which mean profile differs strongly from harmonic one, see Fig. 7. Its saw-like appearance can hardly be explained in terms of dynamo, where all small-amplitude periodic processes are characterized by "smooth" sinusoidal variations of physical values,—see again Ruzmaikin (1985) and references therein. One might only complain of the way dynamos are parameterized,—but without yet a notice of a fundamental lack in a true dynamo process.

As to the plausible *cosmic* origin of the Hale, or Wolf, cycle, we refer here only to an interesting *holographic* relation (following Sanchez et al. 2011) between Bohr radius $r_B = \hbar/\alpha m_e c \approx 5.292 \times 10^{-11}$ m and Hubble radius $R_H = cT_U = 1.307(5) \times 10^{26}$ m of the observable Universe (with the Universe's age $T_U = 13.81(5)$ G-years; cosmological parameters are adopted from Olive et al. 2015):

$$\frac{L_W}{r_B} \approx \left(\frac{R_H}{L_W}\right)^3, \tag{2}$$

where $L_W \equiv cP_W$ is the so-called "Wolf length" (it corresponds to "Hale's length" $L_H \equiv cP_H = 2L_W$).

The idea, which seems to be speculative or rather bizarre, is based on a provocative suggestion about a prevalence—on a cosmic space-time scales—of relations between dimensionless physical and cosmological parameters and fundamental constants above solutions of differential equations.

However, physical mechanism, responsible for relations, similar to (2), is not yet proposed, except the claim that our Universe needs "a holographic and tachyonic approach" (see however discussion of the "cosmic" hypothesis by Sanchez et al. 2011).

6 Conclusion

Our results and reasonings do not deny an importance and efficiency of magnetic dynamo which is often and successfully involved for an explanation of the Sun's cyclic activity. However, that historical and well-founded approach is suited only for exploration of active and cyclic processes taking place at the solar *surface*, in the atmosphere, and does not reveal true causes of the cycle itself and its remarkable long-time phase coherency. As our reviewer rightly pointed out, "... the linkage of the dynamo in the Sun's nothern and southern hemispheres is another issue that is not well understood.". It is why expedient to cite here also Obridko (2008): "... the solar 11-year cycle is perhaps the most well-known quasi-periodic phenomenon of the Sun and, plausibly, in astrophysics at all.". Some authors have made in the past an independent conclusion about *external* source of a "synchronization", or captured character, of solar activity "auto-oscillation" (see, e.g., Rubashev 1964; Kotov et al. 1965); notice also that the semiperiod of the Hale's cycle, ≈ 11 years, was identified a decade ago by Sanchez (2006) as a main cosmic beat note.

The break of GMF at the phase ≈ 0.03 is impressive. One should take into account, however, that the *real* event might cover much shorter time interval than that in Fig. 7: the field jump could be nearly "instantaneous" by cosmic measures (this junmp is clearly seen also in succession of original daily records of observatories). Because for the Sun, owing to its huge, by terrestrial measures, mass and size and due to interference of various "inertial" hydromagnetic processes (they could be governed by dymamo), the *observed* transition, of the magnetized photosphere, might be stretched to ≈ 1 year. The break itself might be a manifestation of a sharp change of the Sun's behaviour, which could be hardly described in terms of classic astrophysics and dynamo theory: both involve smooth waves and oscillations—solutions of differential equations.

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