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Magnetic cycles of the Sun inferred from its mean magnetic field

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ABSTRACT

Over the past 55 years, the Crimean Astrophysical Observatory, the Wilcox Solar Observatory, and five other observatories of the world registered the mean magnetic field of the Sun observed as a star (in all, about 29 thousand daily values of the longitudinal field strength of the visible solar hemisphere were acquired from 1968 through 2022). This field varies with two periods: 21.5(7) years, corresponding to the Hale cycle $P_{\rm H}$ = 22.14(8) years; and a period of 7.08(10) years, which is about three times shorter than $P_{\rm H}$ (the precise ratio, 3.13(5), reminds of the Archimedes approximation, 22:7, of the π number). A special analysis of the solar polar fields (Stanford data for 1976–2022) proves the reality of the magnetic 7-year cycle of the Sun, whose nature is unknown.

Key words: Sun, photosphere, mean magnetic field, 22-year cycle

1 Introduction

The solar mean magnetic field (SMMF) represents the average longitudinal strength B of the visible solar hemisphere. It is measured by the Zeeman effect of a Fraunhofer absorption spectral line, sensitive to the magnetic field registered in the light from the total solar disk. Solar magnetographs used for such measurements must be of high sensitivity, about 0.01–0.15 G, because the SMMF strength is rather small, fluctuating – due to solar rotation, evolution of the large-scale fields, and the Schwabe 11-year cycle – within ±2 G, rarely exceeding these bounds. Note that spots and active regions give no essential contribution to the SMMF variations with time: the B value is mainly determined by vast areas of the quiet solar photosphere.

Regular SMMF measurements started in 1968 at the Crimean Astrophysical Observatory (CrAO; Severny, 1969) were supported by astronomers from six other sites: Mount Wilson Observatory (Sherrer, 1977a), Wilcox Solar Observatory (WSO; see Sherrer, 1977b and *WSO.Stanford.edu*), Sayan Observatory (Irkutsk; Demidov, 2002), Sutherland (Chaplin, 2003), National Solar Observatory (NSO, USA; *SOLIS.NSO.edu/vsm*), and Kislovodsk (Pulkovo Observatory). These data allow us to study the time behavior of the global magnetic Sun since the SMMF, in parallel with activity cycles, reflects fairly well the dynamics and variability of the magnetic Sun observed as a star.

2 SMMF: 1968–2022

Details of the SMMF data from seven observatories are given in Table 1, where N is the number of daily B values, S is the standard deviation of a given dataset, and k is the normalization factor (the Crimean datasets CrAO–1 and CrAO–2 correspond to the measurements performed in the spectral lines of Fe I λ525.02 nm, with Lande factor g = 3, and Fe I λ524.71 nm, g = 2, respectively). Each dataset was multiplied by k to reduce a given set to the common rms value; then all sets were merged into a normalized time series for 1968–2022 with the total amount N = 28 653 of the daily strengths B, with S = 0.61 G and the mean value −0.010(4) G (the uncertainty in brackets approximates the standard error; this *normalized* dataset is analyzed in Sects. 3 and 4).

Table 1. The SMMF measurements for 1968–2022.

Observatory	Years	N	S, G	k
CrAO–1	1968–2018	3890	0.61	0.99
CrAO–2	2001–2018	1863	0.61	0.99
Mount Wilson	1970–1982	2457	0.67	0.90
WSO	1975–2022	14147	0.36	1.68
Sayan	1982–2015	477	0.72	0.84
Sutherland	1992–2001	1988	0.43	1.41
NSO	2003–2017	3536	0.45	1.35
Kislovodsk	2014–2015	295	0.99	0.61
Total[a]	1968–2022	28653	0.61	–

[a]Normalized SMMF series

Positive B values correspond to northern (N) polarity; zero phase, to 0 UT on 1 January 1968; and the power spectra (PS) were computed by the direct Fourier transform.

Merging the SMMF datasets using the rms value as a normalization factor produces a consistent and almost uniform time series (see, e.g., Scherrer and Wilcox, 1983; Kotov, 2006, and references therein). In our case, this fact is proved by nearly identical results obtained on the basis of the two time series: *(i)* the combined data for 1968–2022 from seven observatories, $N = 28\,653$, and *(ii)* the WSO dataset only, 1975–2022, $N = 14\,147$; the latter presents the uniform series with a negligible amount of gaps.

3 Power spectra

The PS of the 55-year combined SMMF dataset computed for low frequencies is shown in Fig. 1a, where a few prominent peaks correspond to the following periods: *(1)* $P'_{\rm H} = 20.4(1.3)$ years, associated with the Hale cycle $P_{\rm H} = 22.14(8)$ years; *(2)* $P_{\rm S} = 10.6(4)$ years, close to the Schwabe cycle $P_{\rm H}/2$; *(3)* $P_7 = 7.09(15)$ years, of unknown origin (see below); *(4)* 1.569(8) years; and *(5)* $P_1 = 1.032(6)$ years and $P_2 = 0.956(3)$ years. (Note that for the test frequencies $\nu \lesssim 0.01\mu$Hz, a real 3σ confidence level, C.L., corresponding to the red noise spectrum $I(\nu) \sim \nu^{-1}$ is located above the dashed line.)

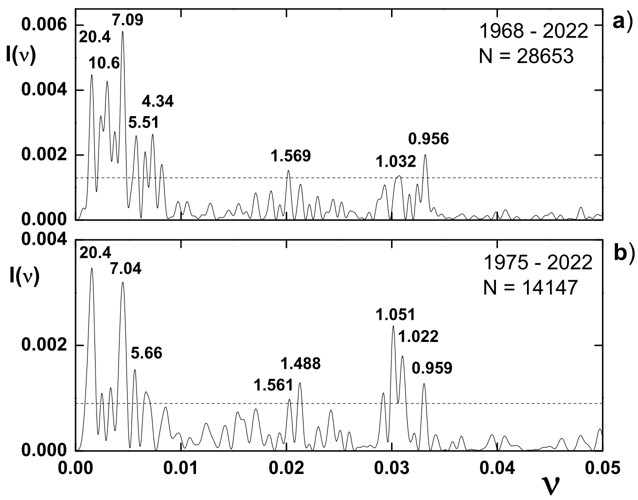

Fig. 1. *(a)* The SMMF power spectrum for low frequencies (1968–2022, $N = 28\,653$). The horizontal axis denotes frequency ν in μHz, and the vertical axis shows power $I(\nu)$ in arbitrary units. The dashed horizontal line indicates a 3σ C.L., and the major peaks are marked by numbers (period in years). *(b)* Same for the WSO data (1975–2022, $N = 14\,147$, see text).

Some opponents (e.g., Scherrer, 2021, private communication) argued that the 55-year time series is too short for the assertion that the Hale cycle is actually present in the SMMF data, and the 7-year peak cannot be distinguished from the third harmonic of the 22-year cycle. One should note, however, that since the Hale magnetic cycle of the Sun is known *a priori* (Severny, 1966), the corresponding probability of its appearance in the SMMF PS plotted in Fig. 1a must not be multiplied by the number of independent test frequencies.

As to the 7-year cycle, the opponents noted that this timescale, close to the third harmonic of $P_{\rm H}$, should be considered as an artifact emerging in the SMMF PS due to a peculiar shape of the SMMF 22-year mean curve (Fig. 2a). To reject this hypothesis, in Sect. 6 we will address to the WSO time series of the polar fields.

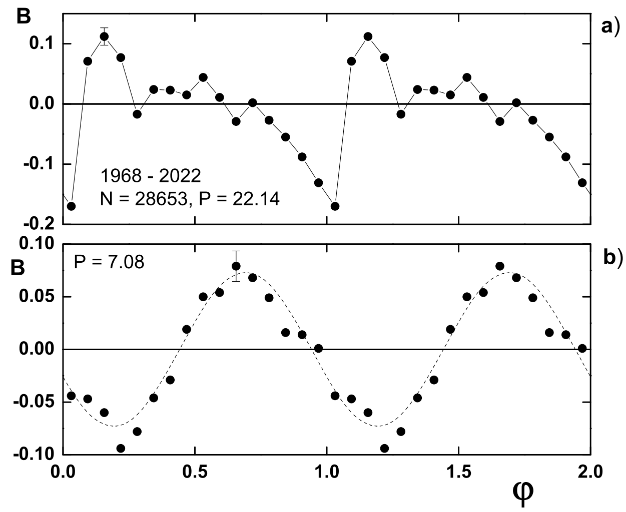

Fig. 2. *(a)* The SMMF variation with a period of 22.14 years (1968–2022, $N = 28\,653$). The horizontal axis denotes phase φ, and the vertical axis shows strength B in G (dots). The vertical bar indicates the typical standard error for each of 16 blocks of data. *(b)* Same for the 7.08-year period, with the best-fit sinusoid shown by the dashed line.

The period $P_1 = 1.032(6)$ years is quite interesting: being close to the Earth orbital period $P_{\rm E} = 1.000$ year, it coincides within the error limits with the synodic period of Saturn, 1.035 years, and also with the average synodic period of four giants, 1.036(20) years. (Many astronomers are quite skeptical about the physical associations of the Sun's variability with the planetary orbits, as interesting as that would be; see, however, Scafetta, 2020.) The other "near-terrestrial" period, $P_2 = 0.956(3)$ years, coincides within the error limits with the beat period of the two timescales, $P_{\rm E}$ and the Hale cycle:

$$\frac{P_{\rm H} P_{\rm E}}{P_{\rm H} + P_{\rm E}} = 0.957(4) \text{ years.} \qquad (1)$$

Note also that *(1)* the beating period of P_1 and P_2, equal to 13.0(1.2) years, agrees within the error limits with the orbital period of Jupiter, 11.9 years (sidereal), being also close to the Schwabe cycle, 11.07(4) years; *(2)* the best period value associated with the prominent peak $P'_{\rm H}$ in Fig. 1a can be defined more correctly – by extrema of the yearly mean B values – as 21.5(7) years; *(3)* the "Schwabe" peak $P_{\rm S}$ is absent in the WSO data; and *(4)* all other noticeable peaks have small statistical significance.

But it is well known that the use of the direct Fourier transform (or the Lomb–Scargle periodogram; see Scargle, 1982) to compute the PS is sometimes risky due to several effects and limitations. In our case, the reliability of Fig. 1a is confirmed by the PS of the WSO data only (the uniform time series for 1975–2022, almost without gaps) plotted in Fig. 1b. The latter shows two prominent peaks of the combined data series, with periods 20.4(1.5) and 7.04(18) years, which agree well with $P'_{\rm H}$ and P_7, respectively (on the origin of the near-annual periodicities see Kotov, 2019).

Below we focus our attention toward two highest peaks with periods $P_7 \approx 7$ and 21–22 years. (For the best P_7 value we get 7.08(10) years, the average of the three values determined by the SMMF measurements by the WSO and other observatories, as well as by the WSO polar field observations, see Sect. 6.)

4 Mean curves

The mean curve of the SMMF variation with the folding period $P_{\rm H}$ plotted in Fig. 2a reveals a saw-tooth shape, with a sharp polarity change at the phase $\varphi \approx 0.06$; the unusual shape of this curve has recently arisen a discussion about the cosmic origin of the Hale cycle (Kotov, 2017, 2020). Note that this particular shape might be the principal cause for the emergence of the peaks (timescales, in years) 10.6(4), 7.09(15), 5.51(9), and 4.34(6) as overtones of the $P'_{\rm H}$ timescale in Fig. 1a: the ratios of $P'_{\rm H}$ (or $P_{\rm H}$) to those timescales occur to be about 2, 3, 4, and 5.

The mean 7.08-year curve, which is nearly sinusoidal, is plotted in Fig. 2b: the harmonic amplitude $A_{\rm h} = 0.07$ G and the phase of the harmonic maximum $\varphi_{\rm h} = 0.69$.

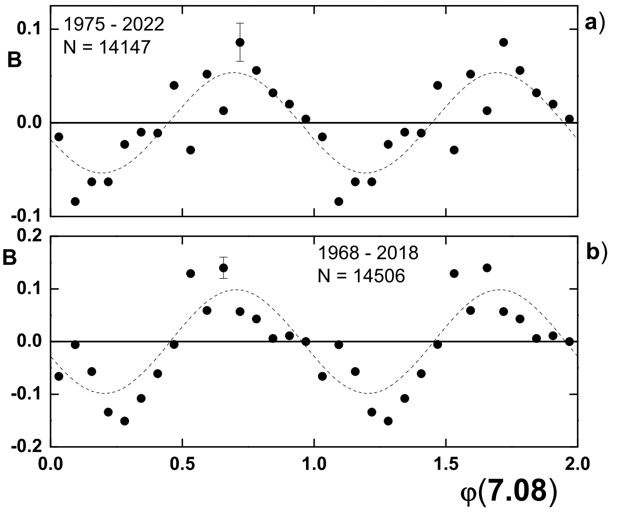

Fig. 3. Same as in Fig. 2b, but for *(a)* the WSO data for 1975–2022, $N = 14\,147$; and *(b)* the data of other observatories for 1968–2018, $N = 14\,506$.

The total SMMF dataset was divided then into two parts: the WSO data only, 1975–2022, and the data of six other observatories, 1968–2018. The resultant phase plots in Fig. 3 confirm the reality of the 7-year magnetic periodicity of the Sun: $\varphi_{\rm h} = 0.70$ for both curves, and $A_{\rm h} = 0.054$ and 0.098 G for the top and bottom ones, respectively (the difference of amplitudes is easily explained by the differences in methods of observations and calibration procedures, as well as sampling).

5 Strange period P_7

There is a special interest to the 7-year periodicity by the two reasons: *(a)* the height of the corresponding peak in Fig. 1 is nearly identical to that of the $P'_{\rm H}$ ($P_{\rm H}$) peak, and *(b)* the ratio of the $P_{\rm H}$ period to P_7 is equal to 3.13(5), i.e., within the error limits to the world constant π.

One immediately reminds of the famous Archimedes approximation 22:7 of the π number. Is it a chance coincidence? It is also well known that some periodic processes of nature are linked to the π number as a geometry factor of our space (see, e.g., Gorobetz, 2004). This is why π enters, for instance, the probability law and the Gaussian distribution; one should also take into account that the ratio $P_{\rm H}/P_7$ happens to be closer to π than to three, with a nearly 2.6σ significance of the deviation from 3.00. (We would like to remind, for instance, the determination of the reduced Plank constant: $\hbar \equiv h/2\pi$ – the unit of the intrinsic angular momentum of a subatomic particle; notations are usual.)

However, the P_7 peak can be much likely explained as the third overtone of the basic $P'_{\rm H}$ cycle: the actual ratio of the two dominant periods appearing in Fig. 1 is equal to 2.9(2); it is thus closer to 3 than to π. In fact, the π number emerges only when using the long-term average 22.14-year for the Hale cycle, but the latter is not shown up in the short-time datasets in Fig. 1. One should note, however, that the simple "3-factor" hypothesis cannot explain the lack of the second harmonic, $P'_{\rm H}/2 \approx 10.5$ years, in the PS of the uniform WSO data, see Fig. 1b.

6 Polar magnetic fields

It is interesting to analyze the time variations of the solar polar fields measured by the WSO nearly each day since 1976 and averaged within 30-day intervals; these data are published with a 10-day sampling for N- and S-poles separately: longitudinal strengths $B_{\rm N}$ and $B_{\rm S}$, respectively (1976–2022, see *WSO.Stanford.edu*).

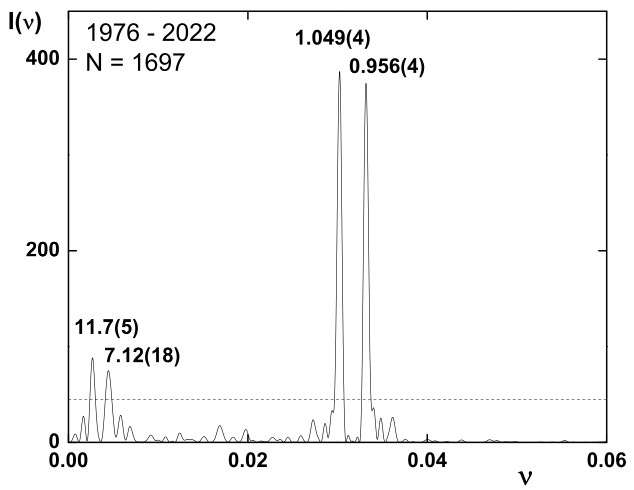

Fig. 4. Same as in Fig. 1, but for the polar fields for 1976–2022, $N = 1697$.

The PS of $N = 1697$ values of the mean polar field $(B_N + B_S)/2$ is shown in Fig. 4, where two major features correspond to periods of 1.049(4) and 0.956(4) years, with a beating timescale of 10.8(7) years (the heights of these peaks correspond to $A_h \approx 0.20$ G in the WSO scale). Their origin is easily explained by the polar field reversals, happened each 11-year cycle, and by the yearly changes of the seeing conditions of the solar poles as observed from Earth (due to a 7.25° deviation of the Sun's axis from the perpendicular to the ecliptic plane, one observes the northern pole of the Sun from 7 June through 7 December, and the southern one – during the rest of a year); theoretical components correspond to 1.047(4) and 0.957(4) years.

Two noticeable peaks at the lowest frequencies in Fig. 4 correspond to periods 11.7(5) and 7.12(18) years, with $A_h \approx 0.09$ G in the WSO scale. While the first peak may be reasonably associated with both the Schwabe 11-year cycle and the Jovian period of 11.9 years, the second peak, of unknown origin, coincides with the above P_7 periodicity (see Fig. 1). By averaging the results for SMMF and polar fields, we specify the period values of our attention: 11.2(3) years, the Schwabe cycle; and $P_7 = 7.08(10)$ years, of unknown nature.

7 Conclusion

Many authors have already concluded that the Hale 22-year cycle is the most fundamental for solar magnetic activity (note, however, that the Schwabe 11-year cycle is the primary one for sunspots and slow variations of the solar irradiance). But if the Hale and Schwabe cycles, along with the new 7-year period, were of cosmic origin (Kotov, 2017), one should look for a mechanism of their emergence on the Sun. For the present, one may advance some hypotheses only.

Our results do not deny importance and efficiency of the magnetic dynamo (along with the α–Ω dynamo model) for the Sun, which is often and successfully addressed for the interpretation of solar cyclic activity. However, this historical and well-founded approach is suited only for exploration of active and cyclic processes taking place on the solar surface, in the Sun's atmosphere, convective zone, and corona and does not reveal true roots of a cycle itself. It seems suitable therefore to cite here Obridko (2008): "... the solar 11-year cycle is perhaps the most well-known quasi-periodic phenomenon on the Sun and plausibly in astrophysics at all." Many authors have made independent conclusions about an enigmatic external source of "synchronization" or "captured character" of the solar active auto-oscillation. (One must also recall the conviction of Dicke, 1978 that some "clock", hidden deep inside the Sun, controls the course of the cycle.)

Note that the SMMF, being a global property of our star, represents not only time variations of the integral of large-scale fields but reflects in fact the global motions of electric charges in the photosphere and the Sun's interior. It seems interesting therefore to search for the 7-year periodicity in other, besides the SMMF measurements, data on the Sun's variability (see, e.g., Frick, 2020); this may be the subject of further investigations.

It is worth mentioning that there is a formal link between the Earth orbital period and the P_7 oscillation:

$$P_7 = \frac{P_E}{\pi - 3}, \tag{2}$$

the equality, with a precision of 0.3%, whose physical meaning is not yet understood. Note also that the beating timescale of the P_7 and P_E periods,

$$\frac{P_7 P_E}{P_7 - P_E} = 425(6)\ \text{days}, \tag{3}$$

coincides within the error limits with the most quoted values, 428–433 days, of the Chandler wobble of the Earth axis (of unknown origin yet; see, e.g., Munk, 1960; Smith, 1981; Malkin, 2010). Lopes (2021) has recently found that the substantial parts of the Earth's polar motion might be a consequence of the evolution of planetary ephemerides; moreover, solar activity and a number of geophysical indices show similar signatures (as to a plausible influence of planets on solar activity and general synchronization of the Solar system, see also Scafetta, 2020).

Taking all above arguments into account, we conclude that the new cycle P_7, seen in the solar SMMF variations, should be explained at the present time as *(a)* the third overtone of the 22-year cycle, or *(b)* the new, of unknown origin, solar magnetic periodicity, which is π times shorter than the Hale cycle.

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