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Letter to the Editor

Periodic oscillations in the north–south asymmetry of the solar magnetic field

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Abstract. We report on significant periodic variations of the magnetic activity between the north and south hemisphere of the Sun. For this purpose, we have investigated the north–south asymmetry of two solar data sets, namely the Kitt Peak synoptic Carrington rotation maps of the photospheric magnetic field (1975–2003) and monthly averaged sunspot areas (1874–2003). Using Fourier and wavelet analysis, we have found a regular pattern of pronounced oscillations with periods of 1.50 ± 0.04 yr, 1.79 ± 0.06 yr and 3.6 ± 0.3 yr in the magnetic flux asymmetry. The former two periods are related to a process which leads to a gradual shift in the excess magnetic flux from north to south or vice versa. Additional periods of 43.4 ± 7.1 yr (twice the magnetic cycle) and 320−329 days were detected in the sunspot asymmetry.

Key words. Sun: photosphere – Sun: magnetic fields – Sun: sunspots – Sun: activity

1. Introduction

The magnetic field of the Sun and its related activity phenomena exhibit periodic variations on various time scales. Proving the existence of real periods has long been of interest, for the insights this may provide into the mechanisms of the formation of magnetic fields. Great efforts have therefore been put into the time series analysis of solar data sets, which are often averaged over the whole visible solar surface. However, a variety of solar activity indices such as flares, filaments, magnetic flux, relative sunspot numbers or sunspot areas show some form of asymmetry between the northern and the southern hemisphere (Reid 1968; Howard 1974; Hansen & Hansen 1975; Roy 1977; Swinson et al. 1986; Verma 1987; Garcia 1990; Verma 1993, 2000; Temmer et al. 2002).

In this analysis, we employ a new and promising approach to investigate the temporal behavior of solar magnetic fields. Instead of applying time series analysis to the data itself, our approach is based on the time series analysis of the north–south asymmetry of the data. For this purpose, the absolute values of the data are separately averaged over the northern and southern hemisphere, the asymmetry between the hemispheres is calculated as a function of time and finally Fourier and wavelet analysis is applied to deduce its temporal variations.

Two standard solar data sets have been analyzed accordingly, namely the synoptic Carrington rotation maps of the solar photospheric magnetic fields (1975–2003) from the National Solar Observatory at Kitt Peak (NSO/KP) and the monthly averaged sunspot areas from the Royal Greenwich Observatory (RGO) from 1874 to 1976, combined with data from the Solar Optical Observing Network (SOON) and the National Oceanic and Atmospheric Administration (NOAA) from 1976 to 2003. Both data sets are available online.

We have revealed a surprisingly regular pattern of pronounced oscillations in the magnetic flux asymmetry with (synodic) periods of 1.50 ± 0.04 yr in the interval 1978–1984, 3.6 ± 0.3 yr (most dominant in the interval 1984–1995, but already present since 1978) and 1.79 ± 0.06 yr (1995–2001). The sign of the asymmetry changed from predominantly positive to predominantly negative during the first interval (which corresponds to a gradual shift in the excess of magnetic flux from north to south) and vice versa during the third interval, while it remained mostly negative during the second interval. The asymmetry calculated from sunspot areas exhibits some additional periods, such as 43 ± 7 yr (twice the magnetic cycle of 22 yr) and 320−330 days. The latter occurred during several solar activity minima. We will discuss the relevance of the detected periods and compare them to previously found results.

2. Data and data analysis

The NSO/Kitt Peak data set consists of 377 synoptic maps and covers Carrington rotations 1625–2007 (February 1975–August 2003). Data gaps are rotations

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1640–1644 and 1854. Each map approximates the magnetic flux density $\Phi(\varphi, \sin\vartheta)$ in the photosphere as a function of heliographic longitude φ and sine latitude ϑ, under the assumption that the magnetic fields are vertical (cf. Worden & Harvey 2000, and references therein). A Carrington rotation corresponds to 27.2753 days.

For each map, we averaged the absolute values $|\Phi(\varphi, \sin\vartheta)|$ over longitude and sine latitude, separately for the north ($0 < \sin\vartheta < 1$) and south ($-1 < \sin\vartheta < 0$). The resulting averaged flux densities $|\Phi|_n$ and $|\Phi|_s$ are shown in Figs. 1a and b as a function of time t. Finally, we calculated for each Carrington rotation the magnetic flux asymmetry Γ_Φ (shown in Fig. 1c):

$$\Gamma_\Phi \equiv \frac{|\Phi|_n - |\Phi|_s}{|\Phi|_n + |\Phi|_s}. \quad (1)$$

The analogous quantity was calculated for the combined RGO/SOON/NOAA sunspot areas (1874–2003). The monthly averaged spot areas for the northern and the southern hemisphere, $A_n(t)$ and $A_s(t)$ respectively, are plotted in Figs. 3a and b. The corresponding asymmetry $\Gamma_A(t) \equiv [A_n(t) - A_s(t)]/[A_n(t) + A_s(t)]$ is shown in Fig. 3c. Please note that no correction factors were applied to $A_n(t)$ and $A_s(t)$ when pooling the data sets (cf. Fligge & Solanki 1997). They would cancel out in Γ_A and can therefore be neglected.

We additionally averaged $A_n(t)$ and $A_s(t)$ over each solar cycle (cf. Verma 2000) and thus calculated the asymmetry for cycles 12–23, yielding Γ_{cycle} shown in Fig. 3d. Two sign reversals occurred during cycles 14 and 21 respectively, and a third could be proceeding in the ongoing cycle 23.

The (scaled) yearly moving averages of the magnetic flux asymmetry Γ_Φ and the spot asymmetry Γ_A are plotted in Fig. 1d over the interval 1975–2003. In general, the qualitative agreement is good, except for the distinctive peak in Γ_A around 1987. This was the minimum between cycles 21 and 22, when only very few sunspots were visible on the southern hemisphere. The oscillatory behavior of both quantities is obvious.

We finally used Fourier and wavelet analysis (cf. Torrence & Compo 1998) to deduce the temporal variations of $\Gamma_\Phi(t)$ and $\Gamma_A(t)$. When stating frequencies or periods, we usually refer to the results derived from the Fourier analysis and they are always synodic. The error in frequency is half the frequency resolution.

3. Results and discussion

3.1. The magnetic flux asymmetry Γ_Φ

The wavelet (WPS) and the Fourier power spectrum (FPS) of Γ_Φ are displayed in Fig. 2. Frequencies where the power in the FPS surpasses the 99.9% significance level against white noise are listed in Table 1 and labeled "A" to "E".

Peak "E" at 21.1 ± 0.6 nHz (corresponding to a period of 1.50 ± 0.04 yr) appears in the WPS over the time interval 1978–1984. This is close to the ~520 d (1.42 yr) period found by Ichimoto et al. (1985) in their analysis of Hα flares for solar cycle 21 (1976–1984).

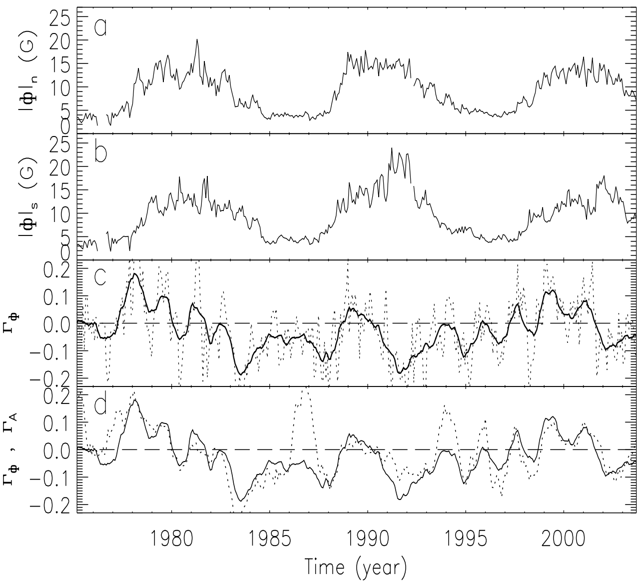

Fig. 1. a) Averaged magnetic flux density $|\Phi|_n$ (in Gauss) for the northern hemisphere vs. time. **b)** Same as **a)** but for the southern hemisphere ($|\Phi|_s$). **c)** The north–south asymmetry Γ_Φ (dashed). The solid line is a moving average calculated with a window of 13 Carrington rotations (≈1 yr). **d)** Comparison of the moving averages of Γ_Φ (solid line) and Γ_A (dashed). The moving average of Γ_A was multiplied by 1/2.

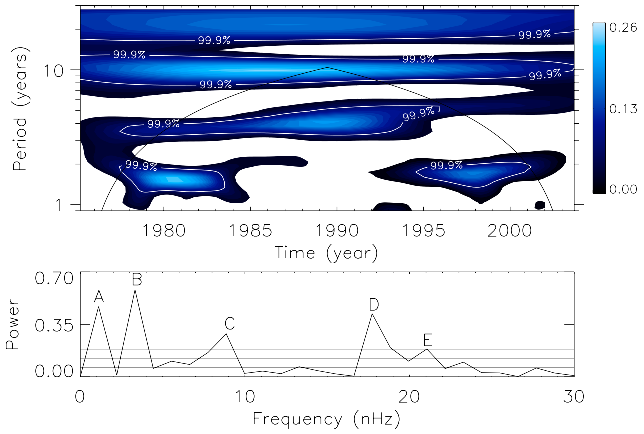

Fig. 2. *Upper panel*: wavelet power spectrum (WPS) of Γ_Φ. Regions with increased power (see color bar) indicate the period of an oscillation (on the y-axis) as well as the time interval over which the oscillation was present (on the x-axis). White contours indicate the 99.9% significance level, black lines the so-called "cone of influence" (Torrence & Compo 1998). *Lower panel*: Fourier power spectrum (FPS) of Γ_Φ. Horizontal lines indicate the 99.9%, 99.0% and 90% significance level (*from top to bottom*). Labeled peaks are listed in Table 1.

Peak "D" at 17.7 ± 0.6 nHz (1.79 ± 0.06 yr) is a dominant feature in the WPS during 1995–2001. Increasing the frequency resolution of the FPS splits "D", the additional peak (not shown) is at 19.2 ± 0.6 nHz (1.65 ± 0.05 yr). Although not discernible in Fig. 2, there is some indication from further wavelet analysis that this additional period blends with the 1.5 yr period in the 1978–1984 interval, lasts over the intervening years 1984–1995, and finally merges into the 1.8 yr

Table 1. Frequencies ν and corresponding periods $T = 1/\nu$ where the power in the Fourier power spectrum of Γ_Φ exceeds the 99.9% level (cf. Fig. 2). The error is half the frequency resolution, i.e. $\Delta\nu = 0.55$ nHz. Values in brackets were computed with a three times higher frequency resolution (peak "D" appeared then as split).

	Freq. (nHz)		Period (yr)	
A	1.1		29	
B	3.3		9.6	
C	8.9	(8.5)	3.6	(3.7)
D	17.7	(17.7/19.2)	1.79	(1.79/1.65)
E	21.1		1.50	

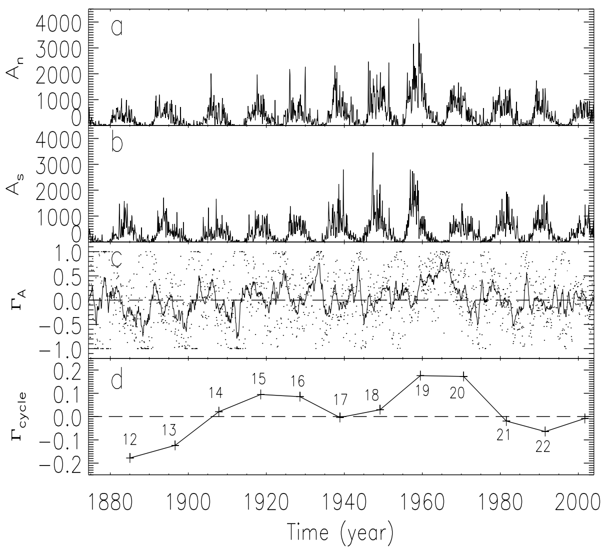

Fig. 3. a) Monthly sunspot area A_n of the northern hemisphere (in millionths) vs. time. **b)** Monthly sunspot area A_s of the southern hemisphere vs. time. **c)** The north–south asymmetry Γ_A vs. time (dots). The solid line is a moving average calculated with a window of 1 yr. **d)** The asymmetry calculated after the sunspot areas were averaged over each cycle (cycle numbers are indicated, cycle 23 is not yet complete).

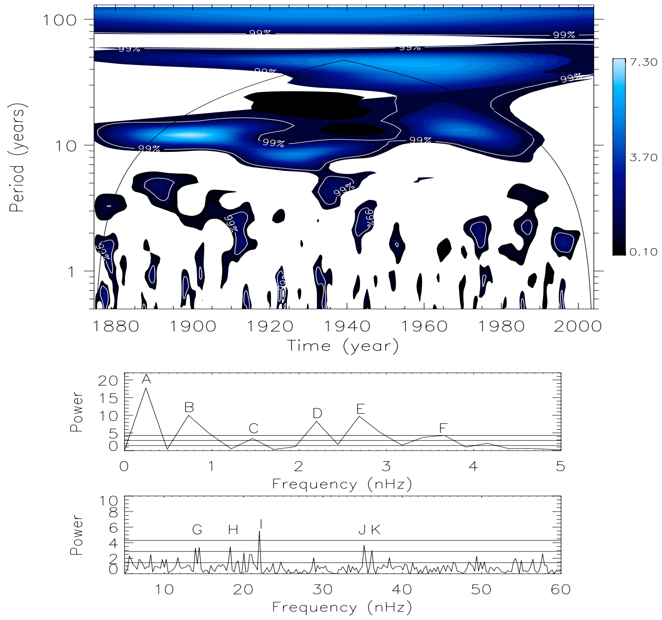

Fig. 4. Same as Fig. 2 but for Γ_A. The upper panel displays the wavelet power spectrum of Γ_A (white contours indicate the 99.0% significance level), the lower panel the Fourier power spectrum (together with the 99.9%, 99.0% and 90% significance levels). Peaks which surpass the 99.0% significance level are labeled "A" to "K" and listed in Table 2.

period in the 1995–2001 interval. Similar periods of ~600 days (1.64 yr) were detected in the variation of coronal hole areas on the southern hemisphere from 1977 to 1989 (McIntosh et al. 1992) and in cosmic ray intensity data from 1947 to 1990 (Valdes-Galicia et al. 1996).

Peak "C" at the approximately halved frequency of 8.9 ± 0.6 nHz (3.6 ± 0.3 yr) is most dominant in the WPS during the interval 1984–1995 (although it actually extends back to 1978). It may be related to the 3.65 yr period reported by Berdyugina & Usoskin (2003) for the southern hemisphere in their analysis of active longitudes of sunspots. Peak "B" at 3.3 ± 0.6 nHz (9.6 ± 1.7 yr) is probably caused by the sunspot cycle and is present in the WPS over the entire period. Peak "A" at 1.1 nHz (29 yr) indicates the existence of a low-frequency oscillation. It cannot be reliably resolved due to the limited length of the time series.

Additional Fourier and wavelet analysis of $|\Phi|_n$ and $|\Phi|_s$ has yielded that both time series exhibit the 1.5 yr period during the interval 1978–1984 (although it is definitely more pronounced for $|\Phi|_n$). The 3.6 yr period is present in $|\Phi|_n$ until ~1990, then disappears in $|\Phi|_n$ but reappears in $|\Phi|_s$. Only $|\Phi|_s$ shows an oscillation with a 1.8 yr period during the interval 1995–2001.

Active regions strongly tend to emerge near or within already existing active regions, forming so-called "complexes of activity". These are maintained by injection of new magnetic flux and may persist from 3–6 up to roughly 20–40 consecutive solar rotations (Gaizauskas et al. 1983, 2001). Therefore, the 1.5 yr and 1.8 yr (and possibly also the 3.6 yr) periods may be related to characteristic lifetimes of such complexes of activity and their independent evolution in one or both hemispheres.

3.2. The sunspot area asymmetry Γ_A

The wavelet and the Fourier power spectrum of Γ_A are displayed in Fig. 4. Frequencies where the power in the Fourier power spectrum surpasses the 99% significance level against white noise are listed in Table 2 and labeled "A" to "K".

In good agreement with Γ_Φ, the power spectra of Γ_A confirm periods of 1.44 ± 0.01 yr over the interval 1980–1985 (peak "I") and 1.73 ± 0.01 yr during 1995–2000 (peak "H"). Increased power can also be seen in the WPS at the period of 3.9 yr during 1982–1992, but only at a low significance level. More power is concentrated around 2.2 yr during the interval 1985–1988 (peak "G"), which is due to the pronounced (and somewhat questionable) peak of Γ_A in 1987 (cf. Fig. 1d).

Interestingly, a period of about 1.7 yr occurs in the WPS of Γ_A during the intervals 1995–2000, 1950–1955 and 1910–1915, which are all 40–45 years apart. A period of roughly 4–5 yr is present (only in the WPS, not in the FPS)

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Table 2. Frequencies ν and corresponding periods $T = 1/\nu$ where the power in the Fourier power spectrum of Γ_A exceeds the 99% level (cf. Fig. 4). The error is $\Delta\nu = 0.12$ nHz.

	Freq. (nHz)	Period (yr)		Freq. (nHz)	Period (yr)
A	0.24	132	F	3.42–3.67	9.3–8.6
B	0.73	43.4	G	14.4	2.20
C	1.47	21.6	H	18.3	1.73
D	2.20	14.4	I	22.0	1.44
E	2.69	11.8	J, K	35.2–36.2	329–320 d

during the intervals 1985–1995, 1935–1945 and 1885–1895, which are 50 years apart. This may be a hint that some periodicities may appear regularly after an intermission of several decades, possibly after twice the magnetic cycle (which has a period of 22 years). In any case, the period of 43 ± 7 yr (peak "B" in the FPS) is a dominant feature in the WPS of Γ_A and it can also be seen in Fig. 3d where the two maxima (and the following minima) are separated by ~45 years.

Moreover, the sunspot cycle with an average period of 11 yr is most likely responsible for peak "'E" at 2.69 ± 0.12 nHz (11.8 ± 0.5 yr), which shows up in the WPS over the interval ~1875–1915. Over the interval 1915–1940, the frequency increased to 3.43−3.67 nHz (9.3−8.6 yr, peak "F") and eventually decreased again during the interval 1960–1985. The wavelet transform for this latter interval yields a period of ~13 yr, whereas the Fourier transform gives 14.4 ± 0.8 yr (peak "D").

Peaks "J" & "K" (329 ± 1 d, 320 ± 1 d) are significant in the WPS of Γ_A during the solar activity minima in 1888–1890, 1921–1923, 1933–1935, 1975–1977 and less distinct in 1952–1954. They are in good agreement with a period of ~320 days found by Lean & Brueckner (1989) in the sunspot blocking function, 10.7 cm radio flux, sunspot number and plage index during solar cycle 21 (1976–1986), in the solar diameter record from 1975 to 1984 (Delache et al. 1985) and in the sunspot number from 1749 to 1979 (Wolff 1983).

4. Summary and conclusions

Both time series under investigation, the magnetic flux (1975–2003) and the monthly sunspot areas (1874–2003), show distinct periodic oscillations between the northern and the southern hemisphere. A list of significant frequencies (in the Fourier domain) can be found in Tables 1 and 2.

Of particular interest are the periods of 1.50 ± 0.04 yr, 3.6 ± 0.3 yr and 1.79 ± 0.06 yr detected in the magnetic flux asymmetry. The first period was present during the time interval 1978–1984, the second during 1978–1995 and the third during 1995–2001. The asymmetry changed from predominantly positive to predominantly negative during the first interval (indicating a gradual shift in the excess of magnetic flux from north to south) and back again during the third interval, while it remained mostly negative from 1984 to 1995 (cf. Fig. 1c). The physical cause for these oscillations is unknown but possibly related to the evolution of complexes of activity and their characteristic lifetimes. Whether or not the period of 3.6 yr is by chance twice as large as 1.79 yr is another open question. It may be related to the 3.65 yr period reported by Berdyugina & Usoskin (2003) for the southern hemisphere in their analysis of active longitudes in sunspot activity. For the 1978–1984 interval, periods of ~1.6 yr and ~1.4 yr were found in the variation of southern coronal holes areas (McIntosh et al. 1992) and in the occurrence of Hα flares (Ichimoto et al. 1985) respectively. Thus we assume that the 1.79 yr period could be corroborated using analogous data for the interval 1995–2001.

The asymmetry calculated from sunspot areas confirms periods of 1.44 ± 0.01 yr and 1.73 ± 0.01 yr for the time intervals 1980–1985 and 1995–2000 respectively. Moreover, two additional significant periodicities of 43.4 ± 7.1 yr (twice the magnetic cycle) and 320–330 days have been found. The former is due to two maxima (and the following minima) in the northern excess of sunspot areas during cycles 15 and 19 (cf. Fig. 3d). The latter was detected in several intervals of low solar activity (i.e. around 1889, 1922, 1934, 1976, and less distinct around 1953). Therefore, this period is most likely of real solar origin and is connected to solar minima. Finally, there is some indication that some oscillations (e.g. with periods of 4–5 yr and 1.7 yr) may occur every 45–50 years in the sunspot asymmetry.

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