Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 40 (2007) 1006–1014
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

Occurrence of the 1.3-year periodicity in the large-scale solar magnetic field for 8 solar cycles

V.N. Obridko *, B.D. Shelting

Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation, Russian Academy of Sciences, Troitsk, Moscow Region 142190, Russia

Received 23 October 2006; received in revised form 26 February 2007; accepted 10 April 2007

Abstract

The data on solar magnetic fields since 1915 have been inferred from H-alpha filament observations. We have used these data together with direct magnetographic observations to study the cycle variation of the large-scale field. Quasi-periodic oscillations with a period of 1.3 years have been detected in the Sun during 8 cycles. They are not present all the time, but are rather seen at maxima and in declining phases of some cycles. No distinct correlation is revealed with the height of the cycle and alternation of the even and odd cycles. Oscillations with a period of 1.3 years are closely associated with quasi-biennial oscillations (QBO) but, occasionally, they occur in anti-phase.

© 2007 COSPAR. Published by Elsevier Ltd. All rights reserved.

Keywords: Large-scale solar magnetic field; 1.3-year oscillations

1. Introduction

In the last decades, the study of cyclic variation of solar activity, i.e., regularities that govern the 11-year and 22-year (magnetic) cycles as a whole, is giving place to a detailed study of their internal fine structure. These investigations have revealed a great number of phenomena whose nature is not entirely clear. Besides the cycle variation, all parameters of solar activity experience quasi-periodic oscillations with shorter periods ranging from seconds to years. Of particular interest are oscillations with a period of the order of 1–2 years. In this paper, we consider quasi-periodic oscillations of the heliospheric equator with a period of 1.3 years.

To begin with, we shall briefly review the literature on the topic. Publications dealing with the oscillation periods of the order of 1.3 years have been grouped by the parameters, in which they are observed. Discussing, first, oscillations in the convection zone, we shall move gradually up the solar atmosphere.

Several studies are devoted to oscillations with a period of 1.3 years revealed at the bottom of the solar convection zone. Komm et al. (2002, 2003, 2004) and Howe et al. (2000) found out that the 1.3-year periodicity at the base of the convection zone is most pronounced in the solar rotation rate at the equator of the tachocline. It is known that the tachocline separates the differentially rotating convection zone and upper atmosphere from the uniformly rotating deep radiative layers. The 1.3-year variation of the solar rotation rate in the vicinity of the tachocline was also revealed by Schou (2003). Komm et al. (2006) and Kosovichev (2003) did not find evidence of the 11-year cycle near the tachocline, where the 1.3-year oscillations of the solar rotation rate were most noticeable. As shown by Christensen-Dalsgaard (2006), the solar rotation is not stationary: regions of faster and slower rotation alternate in the narrow tachocline, with the mean amplitude increasing towards the solar equator. It is also noted that the amplitudes of the rotation rate variation and solar activity cycle correlate (see Toomre et al., 2003). Wolff and Mayr (2004) studied g-modes of the E–W flows and the heat spike at the depth centered at 0.675 solar radii. Near the solar surface, the flows were shown to change direction every 1.3 years. A series of work (McDonald et al., 2005; Cadavid et al.,

---

* Corresponding author.
E-mail address: obridko@izmiran.ru (V.N. Obridko).

0273-1177/$30 © 2007 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2007.04.105

2005) was devoted to the study of quasi-periodicity in fluctuations of the axisymmetric solar magnetic field with the use of the main component and independent component analysis. The discovery of coherent and independent global modes of the magnetic field made it possible to isolate a number of periods and to establish their properties. Thus, oscillation periods of the order of 1.0–1.5 years were considered to be typical of the polar and high-latitude fields and the periods of 1.3 and 1.7 years to characterize the mid- and low-latitude solar events.

The wavelet analysis carried out by Krivova and Solanki (2002) revealed 1.3-year periodicities in the tracers of emerged flux at the solar surface, in particular, sunspots. The power of these variations was observed to vary strongly with time.

Using Mt. Wilson magnetographic data for 1986–1994, in particular, rotation velocity measurements, Javaraiah (2003) found that the 1.3-year periodicity was dominant in the solar surface rotation rate. Özgüç et al. (2003) used the Fourier and wavelet transforms to show that variations with a period of 1.3 years were present in the daily flare index. The analysis covered the time interval from 1966 to 2001. It turned out that the amplitude of short-term oscillations varied strongly with time. Rybák and Karlovský (2003) arrived at a similar conclusion. They isolated a few unstable periodicities in the Wolf number variation for 1850–2002, including the period of 1.3 years, but no cycle dependence was found again. Ikhsanov and Ivanov (2004) revealed the same periodicity in the large-scale solar magnetic field from Stanford (1976–2004) and Kitt Peak (1970–1984) magnetic data. In (Knaack et al., 2005; Knaack and Stenflo, 2005; Knaack, 2005), the spherical harmonic coefficients of the radial magnetic field for axisymmetric and non-axisymmetric modes were calculated from daily magnetograms of the Mt. Wilson and Kitt Peak Observatories, and a few modes were isolated in variations of the photospheric magnetic field. These modes were shown to differ in different activity cycles; e.g., the 1.3-year periodicity is better pronounced in the even (20, 22) than in the odd cycles (21, 23). The authors consider oscillations with the period of 1.3 years to be a single process, which manifests itself at all levels from the tachocline (solar rotation) and photosphere (e.g., areas and numbers of sunspots, large-scale magnetic fields) up to the heliosphere and Earth's magnetosphere (geomagnetic activity).

Mendoza et al. (2006) studied periodicities in different types of the solar magnetic flux (total, closed, open, low, and high latitude open fluxes). All fluxes fluctuate with a period of 1.7 years. The mid-term fluctuation of 1 year is significantly present in total and closed fluxes, but it is less important in open fluxes. Due to the uncertainties involved in estimating the exact period of the quasi-annual peak, the authors could not discriminate it from the 1.3-year periodicity. In their opinion, this high-frequency component is in phase with the 11-year solar cycle.

Many authors reported the periodicities under discussion in various parameters of the solar outer atmosphere and heliosphere and even in geomagnetic disturbances. Using the Fourier analysis, Badalyan and Obridko (2004) found the 1.3-year periodicity in the correlation of the green-line intensity and magnetic field in the lower corona. On the contrary, Kane (2005) did not consider the periodicities of 1.3 and 1.7 years to be prominent in the general spectrum of fluctuations with the periods of 1–3 years. However, his analysis does not seem adequate to us. In their pioneering work, Silverman and Shapiro (1983) carried out a spectral analysis of visual auroras for the period 1721–1943 and revealed a peak near 1.4 years, which was statistically significant, though weaker than the 6- and 12-months peaks known earlier. This variation was found all over the cycle and showed a strong modulation of about 65–68 years and a secular trend. Lockwood (2001) revealed oscillations under discussion in the interplanetary magnetic field and geomagnetic activity, but only after 1940. Two research groups (Richardson et al., 1994; Paularena et al., 1995; Mursula and Zieger, 1999; Mursula and Zieger, 2000; Mursula et al., 2003; Mursula and Vilppola, 2004) isolated oscillation periods from 1.0 to 2.0 years in various phenomena of solar and heliospheric activity and, correspondingly, in the parameters describing those phenomena, such as the interplanetary magnetic field intensity, solar wind velocity, geomagnetic activity characterized by the aa, Ap, and Kp indices, cosmic ray intensity, and luminosity and occurrence rate of auroras. The occurrence rate and amplitude of oscillations differ from cycle to cycle. The 1.3–1.4-year periodicities are more frequently observed and better pronounced in the even cycles 18, 20, and 22, while the period of 1.5 years is dominant in cycle 19, and 1.7 years, in cycle 21 (Mursula and Zieger, 1999; Mursula and Zieger, 2000; Mursula et al., 2003; Mursula and Vilppola, 2004). These periodicities are attributed to evolution of coronal holes that is different in the even and odd cycles. In recent studies (Mursula and Vilppola, 2004), the 1.3-year fluctuations of the solar rotation rate observed at the tachocline are believed to propagate to the solar surface and further, up to 1 AU and higher. These heliospheric periodicities have the solar origin. In particular, oscillations of the aa-index (Mursula et al., 2003) were strong at the middle of the XIX century and since 1930, at the same time as solar activity was high, suggesting correlation with the solar dynamo. Disappearance of the 1.3-year oscillations may be indicative of a long period of low solar activity (Maunder-type minimum).

The periods of 1.7 and 1.3 years were also found in the intensity of cosmic rays in the outer heliosphere (Kato et al., 2003). Kudela et al. (2001) reported cosmic ray intensity variations in the range of 0.5–1.7 years and verified their difference in the odd and even cycles. In particular, the period of 1.7 years was dominant in cycle 21 and the period of 1.3 years in the declining phase of cycles 20 and 22, as found earlier (Mursula and Zieger, 1999, 2000; Mursula and Vilppola, 2004).

Measurements taken near 1 AU during the period 1973–2000 revealed multiple peaks from 0.5 to 9.5 years in the power spectra of the solar wind ion densities and velocities (El-Borie, 2002). Oscillations with a period of 1.3 years were also revealed as a result of wavelet analysis in the IMF, solar wind velocity, and geomagnetic Ap index, which vary with the activity cycle (Prabhakaran Nayar et al., 2002).

Wang and Sheeley suggested that 1.3-year oscillations could be produced by stochastic interaction of local fields and meridional flows (Wang, 2004; Wang and Sheeley, 2003).

It should be noted that the studies using large-scale magnetic field data are necessarily based on relatively short observation series covering 2–3 solar cycles. Direct helioseismic observations are even shorter. An exception is the work by Makarov et al. (2002), in which the authors calculated the photospheric magnetic field by an original method using a long series of observations of H-alpha filaments and prominences from 1915 to 2000. The revealed 1.3-year periodicity in latitudinal oscillations of the zone boundaries of the large-scale magnetic field (neutral lines) was associated with oscillations of the solar rotation rate in the tachocline region. It was shown that this latitudinal oscillation was weak in the period 1950–1970 in N-hemisphere, but was clearly pronounced in 1960 in S-hemisphere. The authors did not find significant correlation of this periodicity with the 11-year cycle.

Gulyaev (2006) has demonstrated that these oscillations coincide with oscillations of the heliospheric current sheet. This result was corroborated by Livshits and Obridko (2006). They studied the behaviour of the effective solar dipole and found out that, at the minimum of the cycle, it is making quasi-precession motions around the solar rotation axis. This quasi-precession lasts from 1 to 3 years. Then, we see a sudden jump during 0.7–1.2 years to the equatorial region, where the dipole continues a smooth precession for another 1.5–3 years. This is followed by a new jump, and the precession continues around the opposite pole. These precession motions may be the cause of the observed oscillations of the heliospheric current sheet.

Livshits and Obridko (2006) analyzed the periodic components of rotation of the effective solar dipole. They found that the dipole changes its direction with time, but its magnetic moment never becomes zero. The dipole moves from being nearly aligned with the solar rotation axis at solar minimum to the plane of the solar equator at solar maximum. The position in the equatorial plane is conventionally called the “horizontal” solar dipole. At other times, the solar dipole can be resolved into the “vertical” (coaxial) and horizontal components. Only two frequencies could be identified in the spectrum of the time variation of the magnetic moments of these dipoles. The quasi-11-year cycle is absolutely similar for the magnetic moments of the horizontal and vertical dipoles. A complete coincidence of period and amplitude indicates that it is, actually, one and the same physical phenomenon, so that the division into two different types of dipoles has no particular physical meaning from the viewpoint of the main solar cycle, and that we are dealing here with the cyclic variation of latitude of the pole of an oblique rotator. The situation is quite different if we consider oscillations with a period of 1.3–2.5 years, so called QBO. These periods are only present in the magnetic moment of the horizontal dipole and are absolutely absent in the case of the vertical dipole.

Obridko and Shelting (2001) and Ivanov et al. (2002) have used a different approach to the problem. They analyzed quasi-periodic oscillations of multipoles of different order. It turned out that quasi-biennial oscillations are best pronounced in quadrupoles and octupoles; i.e., they are more closely associated with the local fields than the effective dipole.

In the recent years, the oscillation periods of 1.3 years in helioseismic measurements have not been as clear as earlier (Howe, 2007). This raises the question of their reliability and of how often they are present in the variation spectrum of various solar parameters. So, we decided to re-consider this problem using data on time variation of the heliospheric current sheet.

2. Wavelet analysis of the tilt of the heliospheric current sheet

We analyze the tilt of the heliospheric equator. A continuous series of the tilt data with a good time resolution for each Carrington rotation (CR) is available for the past 30 years from 1976 to 2006. These data can be downloaded from the Internet site of the Wilcox Solar Observatory.

The first (upper) panel of Fig. 1 illustrates the tilt of the heliospheric equator. It is well known that the tilt becomes nearly zero at solar minima and increases at the cycle maxima (during the field reversal) so that the heliospheric equator passes almost through the pole and the tilt value approaches 90°.

The data were treated using the wavelet Morlet analysis. The wavelet diagram is shown in panel 2 for periods from 1 to 35 CR. The period of 1.2–1.4 years corresponds to 16–19 Carrington rotations; the period of 1.7 years corresponds to 23 rotations, and the period of 2–2.5 years, to 27–33 rotations. Panel 2 represents a wavelet Morlet diagram, on which the coefficients are averaged over 14 rotations. It should be noted that the oscillation amplitudes on panel 2 increase from light to dark regions.

One can see that, at the rise of cycle 21 (1976–1980), the 1.3-year periodicity is weakly pronounced, the period of 1.7 years is stronger, and the period of 2 years is revealed quite distinctly. Then, after the maximum and throughout the declining phase of cycle 21 (1980–1985) and at the beginning of rise phase of cycle 22, the 1.3-year periodicity is becoming stronger, while the 1.7-year oscillations and QBO are vanishing. Over the course of cycle 22 (1985–1995), the 1.3-year periodicity is weak (particularly, at the cycle maximum). In the rise phase of cycle 23, it intensifies sharply until 1998 and, then, vanishes.

Another remark concerns quasi-biennial oscillations (QBO) (two years are equal approximately to 27–33 CR).

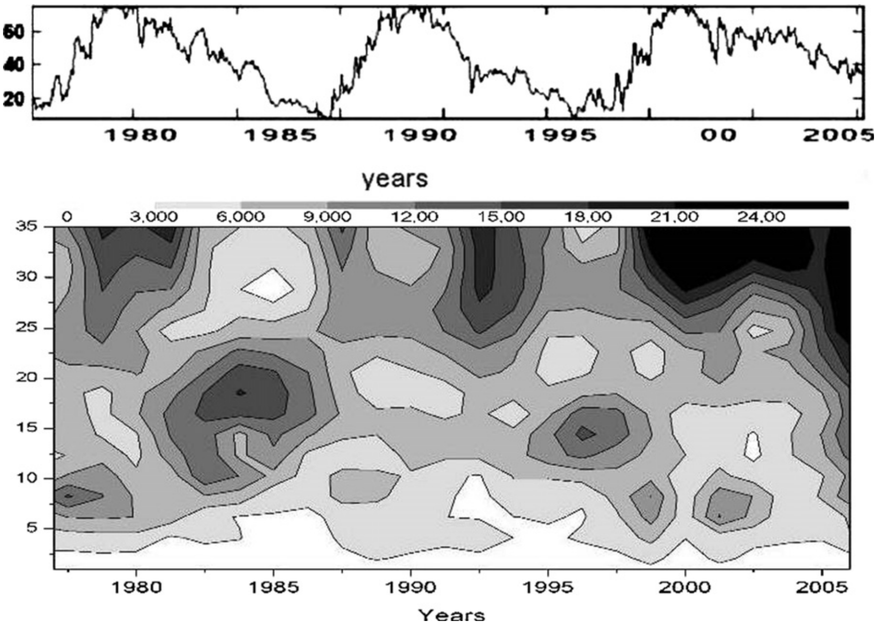

Fig. 1. Wavelet analysis of tilt variations of the heliospheric current sheet. From the top down: the tilt calculated from WSO data (panel 1) and smoothed wavelet diagram (panel 2). The oscillation amplitudes on panel 2 increase from light to dark.

As seen from the wavelet diagram, the enhancement of 1.3-year oscillations is often accompanied by attenuation of QBO and vice versa.

The above conclusions are based on a study of a relatively short time interval of less than 3 solar cycles. It is important to understand whether the regularities revealed are conserved on longer time scales. Therefore, we study the indirect H-alpha magnetic data.

3. Analysis of data for 1915–1996

H-alpha observations of the filament structure made at the Kodaikanal Observatory (India) were placed at our disposal by V.I. Makarov and A.G. Tlatov. These data have been used to calculate the Legendre expansion coefficients $g_l^m(t)$ and $h_l^m(t)$ for the period from 1915 to 1986. The procedure of the expansion is described by Obridko and Shelting (1999). For verification, we have also calculated the polarity of the interplanetary magnetic field (IMF) at 1 AU, using the concept of the source surface and radial expansion of the magnetic field. The results obtained were compared with independent spacecraft observations.

Fig. 2 illustrates an example of such comparison for 1981–1983. Measured and calculated polarities of the interplanetary magnetic field are shown here for every day from 1981.01.22 to 1984.01.08. Data are organized in rows of 27 days long Bartels rotations. The upper left-hand panel shows the magnetic polarities near the Earth reconstructed from ground-based geomagnetic data by the well-known Svalgaard–Mansurov- method. These data calculated from ground-based observations in a single uniform system are available on the Internet site http://www.izmiran.rssi.ru/magnetism/SSIMF/SSIMF/index.htm. The left-hand ordinate provides the calendar years, the right-hand ordinate, the Bartels rotation numbers. The lower left-hand panel represents the results of direct spacecraft observations based on the OMNI data set. The lower right-hand panel illustrates the IMF polarity calculated from WSO measurements of the line-of-sight magnetic field and, finally, the upper right-hand panel shows the IMF polarity calculated from H-alpha data. The same calculation procedure was applied to both WSO and H-alpha data (Obridko and Shelting, 1999). The expansion coefficients $g_l^m(t)$ and $h_l^m(t)$ obtained were used to calculate the daily polarities of the magnetic field at the source-surface. Then, in accordance with the concept of radially expanding solar wind, the daily field polarity near the Earth was found taking into account the standard transport time of 4.5 days.

As seen from the figure, the IMF structure is fairly well reconstructed from H-alpha data. Since this structure is, actually, the manifestation of the tilt and curvature of the heliospheric current sheet, we believe that the calculated Legendre coefficients can also be used to analyze quasi-periodic oscillations. In addition to the early data discussed by Obridko and Shelting (1999), we have calculated the coefficients for 1986–1996, using H-alpha Kislovodsk data. Thus, the full data set covers now 81 years, i.e. 8 solar cycles. With the expansion coefficients available, we can calculate the tilt for each solar rotation.

It is often claimed that WSO observations only extend to 70° of latitude. This is not quite correct. The fact is that the last of the 30 bands of measurements spaced evenly over the sine of latitude is centered at 70°; however, it covers the region from 57° to 90°. Besides, the tilt is not measured directly in the photosphere but is calculated at the source surface from the totality of the measuring points

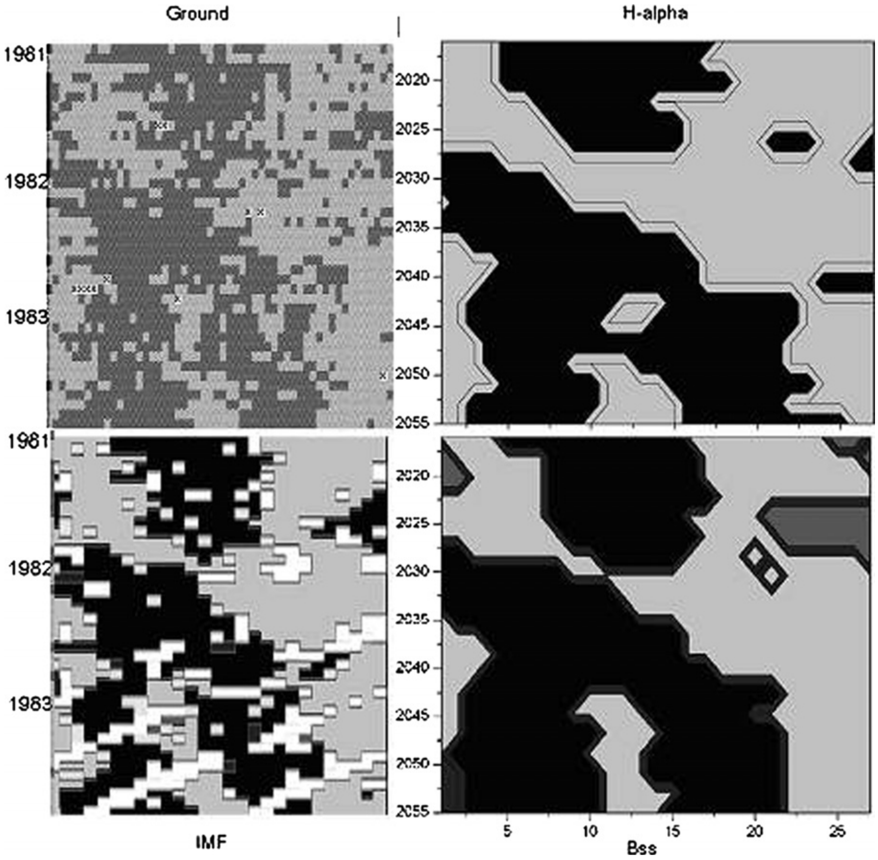

Fig. 2. Comparison of the calculated and measured IMF polarities.

at all latitudes and longitudes. Therefore, the tilt values calculated in the vicinity of the field reversal often exceed 70°. The resolution of H-alpha data obtained near the pole at the same time is somewhat higher, but this has little effect on the sought periodicities.

The calculated tilt values have been filtered to obtain the signal of the 1.3-year period. To do this, we have performed a Fourier expansion and, then, summed up all harmonics in the period range from 8 to 20 CR taking into account their phase. Thus, we have found the signal, which is the sum of the periods from 0.6 to 1.5 years. The 12-month running mean of the signal amplitude is represented by the solid line in Fig. 3. The bold dashed line shows the Wolf numbers. The figure reveals the similar solar cycle variation of the oscillation amplitudes in the range of 0.6–1.5 years and local field variations (except for cycle 18). The agreement is a bit better than in Fig. 1. This is, probably, due to the fact that the frequency band of the signal comprises high-frequency harmonics, which are closely associated with active regions (Ivanov et al., 1998; Anan'ev and Obridko, 1999).

A comprehensive wavelet analysis of the tilt of the heliospheric current sheet from 1915–1996 is presented in Fig. 4. The conventions are the same as in Fig. 1.

As seen from Fig. 4, the 1.3-year periodicity exists most of the time from 1915 to 1996, occasionally enhancing and weakening. The enhancements sometimes coincide with attenuation of QBO and vice versa. Correlation with the 11-year cycle is rather poor, though a little better than in 1927, 1940, 1960, 1970, 1980, and 1996, i.e., in the rise phase and at maximum of the odd cycles and in the even cycle 20. In cycles 20 and 21, the 1.3-year periodicity forms part of the oscillation packet with the periods ranging from 1.2 to 2.0 years. One can also see a secular wave in the effective period: in the middle of the XX century, the band of the effective periods shifts from 16–17 CR (1.3 years) to 20–22 CR (over 1.6 years). Note also that QBO do not form a single band on the wavelet diagram. They are enhanced at the cycle maxima, particularly, in cycles 16, 17, 20, and 21. In the higher cycles 18 and 19, QBO are less prominent.

In order to analyze the correlation with solar activity, we have plotted the time dependence of the absolute values of the 1.3-year wavelet Morlet coefficients (Fig. 5). In fact, this depicts a section of panel 2 of Figs. 1 and 4 at 17 CR (i.e., 1.27 year). The thin curve is based on H-alpha data; the thick curve represents the corresponding results obtained from WSO data. The abscissa shows the years and the maxima of the corresponding solar cycles. It should be noted that such representation does not give clear idea of whether the 1.3-year oscillations form an isolated peak or exist among other oscillations in the range of 1–2 years. Therefore, it must be considered together with Figs. 1 and 4.

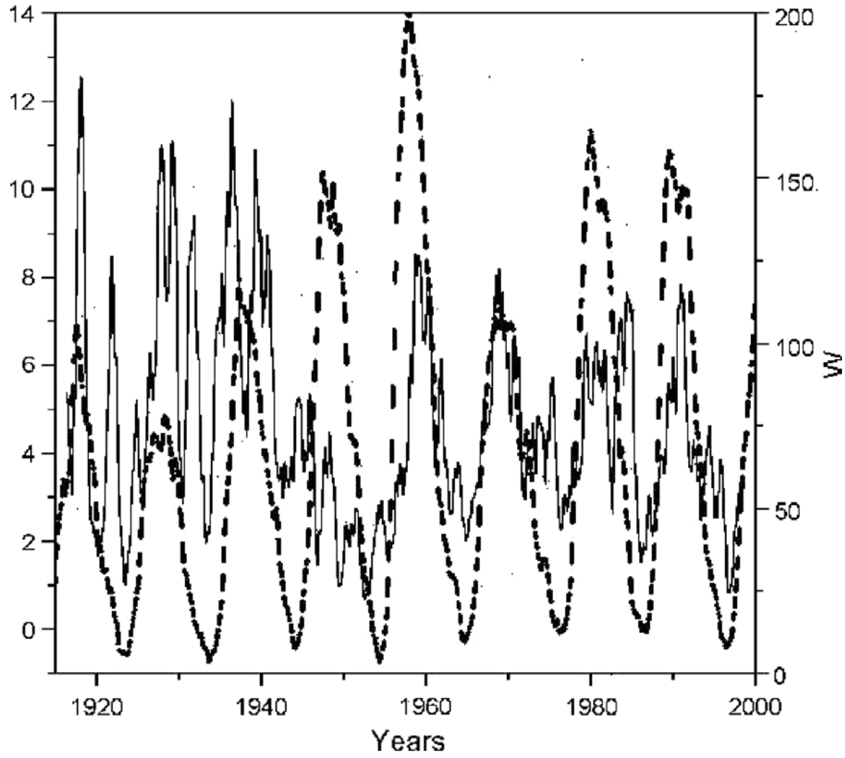

Fig. 3. Comparison of the 8–20 CR signal, which is the sum of the periods from 0.6 to 1.5 years (solid line) and the Wolf numbers (bold dashed line).

Fig. 5, as well as Fig. 2 above, reveals undoubted genetic affinity between 1.3-year oscillations and activity cycles. However, this relation is not unambiguous. As a rule, the oscillation maxima lag somewhat behind the Wolf number maxima, which implies that oscillations with a period of 1.3 years intensify in the declining phase, just when the global field indices increase (Obridko and Shelting, 1992). This agrees, in particular, with the conclusion made by Mursula and Zieger (2000) concerning the relationship between the 1.3-year periodicity and evolution of coronal holes.

The heights of the oscillation peaks do not correlate with the heights of the corresponding sunspot maxima. For some unknown reason, maximum 22 is clearly revealed in H-alpha but is absent in WSO data. However, the oscillation periods of 15 and 19 CR in WSO data are seen in Fig. 1 (panel 2). Apparently, we had to consider a broader oscillation band than merely 17 CR when plotting Fig. 5. These distinctions confirm that, in spite of its global nature, the 1.3-year periodicity is a complicated phenomenon, which shows up differently in different indices. Significant differences between the mid-term quasi-periodicities in cycles 21 and 22 were reported by Mursula and Vilppola (2004).

4. Conclusions

The conclusions from our analysis are as follows:

1. Quasi-periodic oscillations with a period of 1.3 years have been detected on the Sun during the past 8 cycles.
2. However, they are not present all the time, but rather at maxima and in declining phases of the activity cycles.
3. It is obvious that QBO and oscillations with a period of 1.3 years are closely associated.
4. The oscillation frequency naturally changes with time between 12 and 20 Carrington rotations. It should be emphasized again that oscillations with the periods ranging from 6 months to 3 years are very unstable and display frequent distortions. They are rather a sequence of pulses following at fixed time intervals than harmonic oscillations. Therefore, the Fourier transform or any other method analyzing the integral spectrum over a large time window may miss these oscillations. This is, probably, why Basu and Antia (2001) did not find reliable peaks in the vicinity of 1.3 years. Silverman and Shapiro (1983) revealed 1.4-year peaks in the aurora data set for 1721–1943. Besides, it should be noted that we are dealing with the tilt, i.e., a parameter characterizing the structure of the global magnetic field, in which the field intensity is absolutely ruled out. This suggests that the indices associated with the energy of the process and those determined by the field polarity alone may give somewhat different spectra. Comparison of the spectra could provide us with a clue to understanding the origin of these oscillations.

The quasi-periodicities of ~1–2 years are attributed to the effect of flux transport, which causes the horizontal dipole to decay on the meridional flow (Wang and Sheeley, 2003; Wang, 2004). This agrees on the whole with the fact that 1.3-year oscillations are revealed in the horizontal dipole and are not seen in the vertical one (Livshits and Obridko, 2006). However, this model disagrees with the

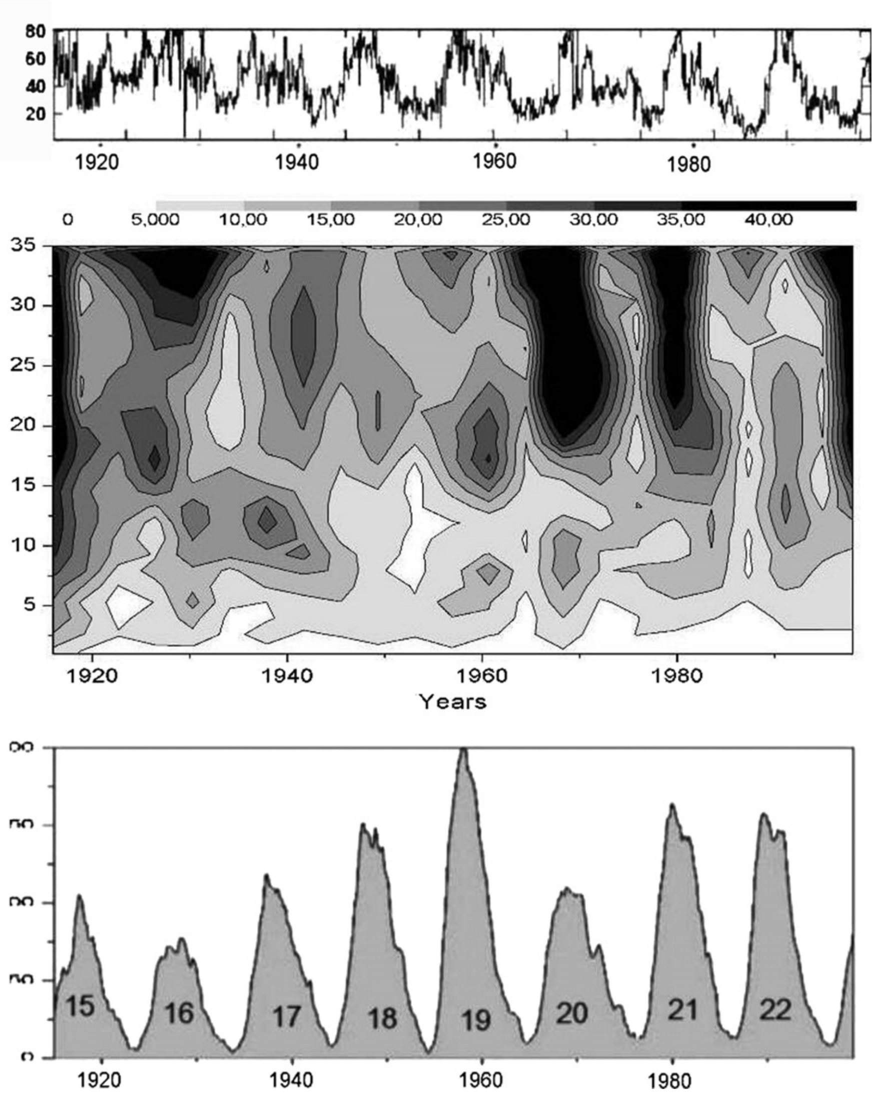

Fig. 4. Wavelet analysis of the tilt of the heliospheric equator for the period 1915–1996. From the top down: the tilt calculated from H-alpha data (panel 1); smoothed wavelet diagram (panel 2); and Wolf numbers (panel 3). The oscillation amplitudes on panel 2 increase from light to dark.

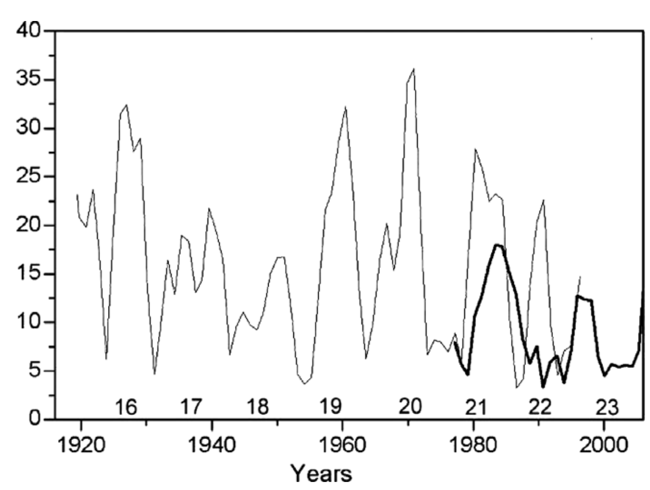

Fig. 5. Time dependence of the absolute values of the 1.3-year (17 CR) wavelet Morlet coefficients. Thin curve shows the results based on H-alpha observations, thick curve based on WSO observations.

results cited above, in Section 1, that show the existence of the 1.3-year periodicity in various indices at all levels from the tachocline to the Earth. It is difficult to understand how the transport of matter and field in the surface layers of the Sun could affect the rotation characteristics at the base of the convection zone. More reasonable seems the idea that 1.3-year oscillations are generated at the tachocline and are an inherent feature of the global magnetic field. It is obvious that a connection exists between the amplitude of mid-term quasi-periodicities and the strength of the solar dynamo.

Acknowledgements

We are grateful to the reviewers for very valuable remarks. The work was supported by the Russian Foundation for Basic Research (projects no. 05-02-16090 and no. 05-02-17251).

References

Anan'ev, I.V., Obridko, V.N. Studies of the rotation periods of photospheric magnetic fields in the 20th–22nd solar cycles. Astron. Rep. 43 (12), 831–845, 1999.

Badalyan, O.G., Obridko, V.N. Solar magnetic fields and the intensity of the green coronal line. Astron. Rep. 48 (8), 678–687, 2004.

Basu, S., Antia, H.M. A study of temporal variations of the tachocline, in: Helio and Asteroseismology at the Dawn of the Millenium. Proc. SOHO 10/GONG 2000 Workshop, Santa Cruz de Tenerife, 2–6 October 2000, ESA SP-464, 297–300, 2001.

Cadavid, A.C., Lawrence, J.K., McDonald, D.P., Ruzmaikin, A. Independent global modes of solar magnetic field fluctuations. Solar Phys. 226 (2), 359–376, 2005.

Christensen-Dalsgaard, J. Rotation of the solar convective zone from helioseismology (abstract), in: Convection in Astrophysics, International Astronomical Union. Symposium no. 239, held 21–25 August, 2006 in Prague, Czech Republic, 30, 2006.

El-Borie, M.A. On long-term periodicities in the solar-wind ion density and speed measurements during the period 1973–2000. Solar Phys. 208 (2), 345–358, 2002.

Gulyaev, R.A. On the oscillatory motions of the principal plane of the solar corona. Solar Syst. Res. 40 (4), 368–371, 2006.

Howe, R., Christensen-Dalsgaard, J., Hill, F., Komm, R., Schou, J., Thompson, M.J., Toomre, J. Temporal variations in solar rotation at the bottom of the convection zone: the current status. Adv. Space Res. 2007.

Howe, R., Christensen-Dalsgaard, J., Hill, F., Komm, R.W., Larsen, R.M., Schou, J., Thompson, M.J., Toomre, J. Dynamic variations at the base of the solar convection zone. Science 287 (5462), 2456–2460, 2000.

Ikhsanov, R.N., Ivanov, V.G. Quasi-annual variations in evolution of large-scale solar magnetic field, in: Stepanov, A.V., Benevolenskaya, E.E., Kosovichev, A.G. (Eds.), Multi-Wavelength Investigations of Solar Activity. Cambridge University Press, Cambridge, UK, IAU Symposium, vol. 223, pp. 629–630, 2004.

Ivanov, E.V., Obridko, V.N., Anan'ev, I.V. Variations of solar irradiance, 10.7 cm radio flux, He I 10830 Å equivalent width, and global magnetic field intensity and their relation to large-scale solar magnetic field structure. Solar Phys. 177, 217–228, 1998.

Ivanov, E.V., Obridko, V.N., Shelting, B.D. Quasi-biennial oscillations of the solar magnetic fields, in: Wilson, A. (Ed.), Solar variability: from core to outer frontiers. The 10th European Solar Physics Meeting, 9–14 September 2002, Prague, Czech Republic. ESA SP-506, v. 2. Noordwijk: ESA Publications Division, ISBN 92-9092-816-6, pp. 847–850, 2002.

Javaraiah, J. '1.3-Year' and '153-day' periodicities in the Sun's surface rotation. Bull. Astron. Soc. India 31, 317–318, 2003.

Kane, R.P. Short-term periodicities in solar indices. Solar Phys. 227 (1), 155–175, 2005.

Kato, C., Munakata, K., Yasue, S., Inoue, K., McDonald, F.B. A ~1.7-year quasi-periodicity in cosmic ray intensity variation observed in the outer heliosphere. J. Geophys. Res. 108 (A10), 1–4, 2003.

Knaack, R. Global evolution of magnetic fields in the photosphere of the Sun during cycles 20–23. Ph.D dissertation, 2005. 179 pages; Dr.sc.nat. Switzerland: Eidgenoessische Technische Hochschule Zuerich (Switzerland); 2005. Publication number: AAT C820734. DAI-C 66/03, p. 653, Fall 2005.

Knaack, R., Stenflo, J.O. Spherical harmonic decomposition of solar magnetic fields. Astron. Astrophys. 438 (1), 349–363, 2005.

Knaack, R., Stenflo, J.O., Berdyugina, S.V. Evolution and rotation of large-scale photospheric magnetic fields of the Sun during cycles 21–23. Periodicities, north-south asymmetries and r-mode signatures. Astron. Astrophys. 438 (3), 1067–1082, 2005.

Komm, R., Howe, R., Durney, B., Hill, F. Temporal variation of angular momentum in the solar convection zone (abstract). Bull. Am. Astron. Soc. 34, 644, 2002.

Komm, R., Howe, R., Durney, B.R., Hill, F. variation of angular momentum in the solar convection zone. Astrophys. J. 586 (1), 650–662, 2003.

Komm, R., Howe, R., Hill, F. Helioseismic sensing of the solar cycle, in: COSPAR Scientific Assembly, held 18–25 July 2004, Paris, France, p. 1397, 2004.

Komm, R., Howe, R., Hill, F. Helioseismic sensing of the solar cycle. Adv. Space Res. 38 (5), 845–855, 2006.

Kosovichev, A.G. What helioseismology teaches us about the Sun, in: Wilson, A. (Ed.), Solar variability as an input to the Earth's environment. International Solar Cycle Studies (ISCS) Symposium, 23–28 June 2003, Tatranská Lomnica, Slovak Republic. ESA SP-535, Noordwijk: ESA Publications Division, ISBN 92-9092-845-X, pp. 795–806, 2003.

Krivova, N.A., Solanki, S.K. The 1.3-year and 156-day periodicities in sunspot data: wavelet analysis suggests a common origin. Astron. Astrophys. 394, 701–706, 2002.

Kudela, K., Storini, M., Rybak, J., Antalova, A. On the wavelet approach to cosmic ray variability (abstract), in: Proc. 27th International Cosmic Ray Conference, 07–15 August, 2001. Hamburg, Germany. Under the auspices of the International Union of Pure and Applied Physics (IUPAP), p. 3773, 2001.

Livshits, I.M., Obridko, V.N. Variations of the dipole magnetic moment of the Sun during the solar activity cycle. Astronomicheskii zhurnal 83 (11), 1031–1041 (in Russian) (to be published in Astron. Rep.), 2006.

Lockwood, M. Long-term variations in the magnetic fields of the Sun and the heliosphere: their origin, effects, and implications. J. Geophys. Res. 106 (A8), 16021–16038, 2001.

Makarov, V.I., Tavastsherna, K.S., Tlatov, A.G., Callebaut, D.K. Secular variation of 1.3-year latitude oscillations of magnetic zone boundaries during 1915–2000, in: Wilson, A. (Ed.), Solar variability: from core to outer frontiers. The 10th European Solar Physics Meeting, 9–14 September 2002, Prague, Czech Republic. ESA SP-506, vol. 1. Noordwijk: ESA Publications Division, ISBN 92-9092-816-6, 2002, p. 173–176, 2002.

McDonald, D.P., Cadavid, A.C., Lawrence, J.K., Ruzmaikin, A. Quasi periodicities in the fluctuations of the axisymmetric solar magnetic field from independent component analysis, in : American Geophysical Union, Spring Meeting 2005, abstract SP43B-05, 2005.

Mendoza, B., Velasco, V.M., Valdés-Galicia, J.F. Mid-term periodicities in the solar magnetic flux. Solar Phys. 233 (2), 319–330, 2006.

Mursula, K., Zieger, B. Simultaneous occurrence of mid-term periodicities in solar wind speed, geomagnetic activity and cosmic rays, in: Kieda, D., Salamon, M., Dingus, B. (Eds.), Proc. 26th International Cosmic Ray Conference. August 17–25, 1999. Salt Lake City, Utah, USA. Under the auspices of the International Union of Pure and Applied Physics (IUPAP), vol. 7, p.123–126, 1999.

Mursula, K., Zieger, B. The 1.3-year variation in solar wind speed and geomagnetic activity. Adv. Space Res. 25 (9), 1939–1942, 2000.

Mursula, K., Zieger, B., Vilppola, J.H. Mid-term quasi-periodicities in geomagnetic activity during the last 15 solar cycles: connection to solar dynamo strength to the memory of Karolen I. Paularena (1957–2001). Solar Phys. 212 (1), 201–207, 2003.

Mursula, K., Vilppola, J.H. Fluctuations of the solar dynamo observed in the solar wind and interplanetary magnetic field at 1 au and in the outer heliosphere. Solar Phys. 221 (2), 337–349, 2004.

Obridko, V.N., Shelting, B.D. Cyclic variation of the global magnetic field indices. Solar Phys. 137 (1), 167–177, 1992.

Obridko, V.N., Shelting, B.D. Structure of the heliospheric current sheet derived for the interval 1915–1986. Solar Phys. 184, 187–200, 1999.

Obridko, V.N., Shelting, B.D. Quasi-biennial oscillations of the global solar magnetic field. Astron. Rep. 45 (12), 1012–1017, 2001.

Özgüç, A., Ataç, T., Rybák, J. Temporal variability of the flare index (1966–2001). Solar Phys. 214 (2), 375–396, 2003.

Paularena, K.I., Szabo, A., Richardson, J.D. Coincident 1.3-year periodicities in the ap geomagnetic index and the solar wind. Geophys. Res. Lett. 22 (21), 3001–3004, 1995.

Prabhakaran Nayar, S.R., Radhika, V.N., Revathy, K., Ramadas, V. Wavelet analysis of solar, solar wind and geomagnetic parameters. Solar Phys. 208 (2), 359–373, 2002.

Richardson, J.D., Paularena, K.I., Belcher, J.W., Lazarus, A.J. Solar wind oscillations with a 1.3 year period. Geophys. Res. Lett. 21 (14), 1559–1560, 1994.

Rybák, J., Karlovský, V. Mutual relations of the intermediate periodicities of the Wolf sunspot number, in: Wilson, A. (Ed.), Solar variability as an input to the Earth's environment. International Solar Cycle Studies (ISCS) Symposium, 23–28 June 2003, Tatranská Lomnica, Slovak Republic. ESA SP-535, Noordwijk: ESA Publications Division, ISBN 92-9092-845-X, pp. 145–148, 2003.

Schou, J. Time variations of meridional and zonal flows (abstract). Bull. Am. Astron. Soc. 35, 854, 2003.

Silverman, S.M., Shapiro, R. Power spectral analysis of auroral occurrence frequency. J. Geophys. Res. 88, 6310–6316, 1983.

Toomre, J., Christensen-Dalsgaard, J., Hill, F., et al. Transient oscillations near the solar tachocline, in: Sawaya-Lacoste, H. (Ed.), Local and global helioseismology: the present and future. Proc. SOHO 12 / GONG+ 2002, 27 October–1 November 2002, Big Bear Lake, CA, USA, ESA SP-517, Noordwijk, Netherlands: ESA Publications Division, ISBN 92-9092-827-1, p. 409–412, 2003.

Wang, Y.-M. The Sun's large-scale magnetic field and its long-term evolution. Solar Phys. 224 (1–2), 21–35, 2004.

Wang, Y.-M., Sheeley Jr., N.R. On the fluctuating component of the Sun's large-scale magnetic field. Astrophys. J. 590 (2), 1111–1120, 2003.

Wolff, C.L., Mayr, H.G. The Sun's reversing flows and heat spike as caused by g-modes. Astrophys. J. 606 (2), L163–L166, 2004.