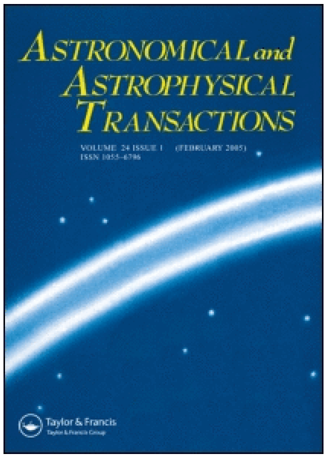


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# QUASI-BIENNIAL OSCILLATIONS OF THE SOLAR GLOBAL MAGNETIC FIELD

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This work continues the series of papers analyzing the nature of the large-scale solar magnetic field (LSSMF) over a long time interval (1915–1990). We used the data inferred from observations of $H_\alpha$ filaments. SWAN and WAVELET analyses show that Quasibiennial Oscillations are connected with the lowest multipoles, in other words, with the global part of the LSSMF. For multipoles with number larger than 4 the power of the spectrum in the range of 2–3 years decreases abruptly. The LSSMF zonal and sectorial components (both odd and even) were calculated and the Fourier spectra were obtained. This allowed us to compare the amplitudes of different harmonics. Quasi-biennial oscillations are best pronounced in the odd sectorial structures. QBO are absent at the cycle minima in the spectra based on the Stanford data (i.e., with the field strength taken into account). Contrary to that, QBO are of the same order over the entire time interval in the spectra based on H$\alpha$ data (i.e., where the field structure is emphasized).

KEY WORDS Solar magnetic field, solar cycle, quasi-biennial oscillations

## 1 INTRODUCTION

With this work, we continue our investigations of the origin and behavior of the large-scale solar magnetic field (LSSMF) over a long time scale (1915–1999). The data were derived from H$\alpha$ observations using the method suggested by Obridko and Shelting, (1997; 1998; 1999; 2000a,b). The main task of the paper is to discuss in more detail one of the aspects of LSSMF behavior and evolution, namely, the 2–3 year quasi-periodic or quasi-biennial oscillations (QBO).

Many investigators have observed QBO using various solar features and indices, and the results obtained have been widely described in literature. This oscillation mode was revealed in solar activity variations in the polar zones (Benevolenskaya and Makarov, 1991; Makarov *et al.*, 1991), in parameters of large-scale magnetic fields (Ivanov, 1991), in dynamics of sunspot indices (Kuklin and Plyusnina, 1991) and of sunspot number in long-lived complexes of activity (Ivanov, 1986), and in geomagnetic activity (Ivanov-Kholodny and Chertoprud, 1991; Ponyavin, 1991). It should be noted that QBO were also discovered in the magnetic field of the Sun as a star (Rivin and Obridko, 1992), in the solar neutrino flux (Obridko and Rivin, 1995, 1996), in the shift of the magnetic neutral lines (Makarov *et al.*, 1998), in the Earth's stratosphere (Labitzke and Van Loon, 1993) (although it is not clear if they are related to solar oscillations), and in the solar irradiance (Ivanov-Kholodny *et al.*, 2000; Wilson and Mordvinov, 1999).

## 2 QBO IN THE SECTOR STRUCTURE

As shown in our previous work (Obridko and Shelting, 2000a,b), QBO are best pronounced in the 4-sector structure, especially near the solar cyclic phases 0.1, 0.35, 0.7, and 0.9, where the 4-sector structure prevails over the 2-sector one. It is difficult to say whether these maxima are associated with the corresponding reference points of the cycle or are the result of quasi-periodic fluctuations with characteristic periods of 2–3 years. Four reference points are present in every cycle. The change of activity both at these points and at the maxima and minima of the cycle can be interpreted as QBO. However, it is possible that, on the contrary, QBO stimulate sharp changes in solar activity that we take for the reference points of the cycle.

QBO are particularly pronounced in the difference of rotation periods of the 2- and 4-sector structures (T2–T4), where they are much more noticeable than the 11-year periodicity, and especially in the spectrum of this difference at all latitudes. QBO of this type change their properties very slowly and display no dependence on the phase of the solar cycle. The intensity of oscillations does not depend on latitude and seems to have quasi-solid behavior. This fact is likely to imply a large depth of the QBO generation region.

The 11-year periodicity is likely to be a proper resonant frequency of the LSSMF generation region. The 11-year variations coincide in phase at both levels where the 2- and 4-sector structures originate. Therefore, they become weaker after subtraction of the rotation periods T2–T4. The wave phases of QBO at these two levels are different, which may be a simple mathematical consequence of the fact that the period of QBO is much shorter than 11 years. A more comprehensive physical explanation is possible, however, if QBO are treated as propagating waves generated far below the levels of origin of the 2- and 4-sector structures. The phase difference between oscillations at these levels is natural, and, therefore, the oscillations are still observed after subtraction of the rotation periods.

Quasi-biennial LSSMF oscillations are analyzed here with the main objective to establish their dependence on the scale and structure of the field. The magnetic moments of multipoles of different order are calculated to show that QBO are observed in the lowest modes only (Section 3). This means that QBO have a global nature. In Section 4 below, we changed the data format to discuss the zonal and sectorial structures separately. It turned out that QBO were more typical of the sectorial than of the zonal structure. In addition to that, we analyzed oscillations of the magnetic moments of the 'vertical' (with the axis parallel with the solar rotation axis) and 'horizontal' (with the axis in the plane of the solar equator) effective

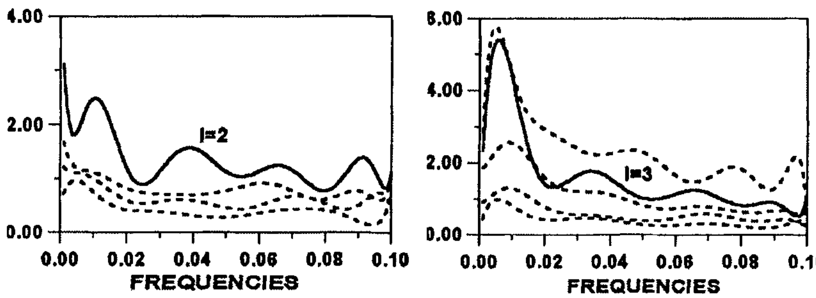


**Figure 1** The Fourier spectrum of the magnetic moments.

dipoles (Section 5). The manifestation of QBO in the vertical and horizontal dipoles is about the same as in the zonal and sectorial structures, respectively.

## 3 QBO MANIFESTED IN VARIATIONS OF THE LSSMF MAGNETIC MOMENTS

The data on LSSMF were derived by our special method (Obridko and Shelting, 1997, 1999; 1998) from the $H_\alpha$ synoptic maps for 1915–1990 and were compared with the Stanford data for the same period (Hoeksema and Scherrer, 1986; Hoeksema, 1991).

The magnetic field on the solar surface can be written in the form of expansion in spherical harmonics as a function of co-latitude $\vartheta$ and longitude $\lambda$

$$\begin{aligned} B_r &= \sum P_l^m(\cos\vartheta)(g_l^m \cos m\lambda + h_l^m \sin m\lambda)((l+1)(R_0/R)^{l+2} - l(R/R_s)^{l-1}c_l), \\ B_\vartheta &= \sum \frac{\partial P_l^m(\cos\vartheta)}{\partial\vartheta}(g_l^m \cos m\lambda + h_l^m \sin m\lambda)((R_0/R)^{l+2} + (R/R_s)^{l-1}c_l), \\ B_\lambda &= -\sum \frac{m}{\sin\vartheta} P_l^m(\cos\vartheta)(h_l^m \cos m\lambda - g_l^m \sin m\lambda)((R_0/R)^{l+2} + (R/R_s)^{l-1}c_l), \end{aligned} \tag{1}$$

where $P_l^m$ is the associated Legendre polynomial. The expansion coefficients $g_l^m$ and $h_l^m$ are determined by integration over the surface

$$g_l^m = \frac{(2l+1)}{2\pi}\frac{(1-m)!}{(1+m)!}\int_0^{2\pi} d\lambda \cos(m\lambda)\int_0^{\pi} B_r(\vartheta,\lambda)P_l^m\cos(\vartheta)\sin(\vartheta)\,d\vartheta,$$

$$h_l^m = \frac{(2l+1)}{2\pi}\frac{(1-m)!}{(1+m)!}\int_0^{2\pi} d\lambda \sin(m\lambda)\int_0^{\pi} B_r(\vartheta,\lambda)P_l^m\cos(\vartheta)\sin(\vartheta)\,d\vartheta,$$

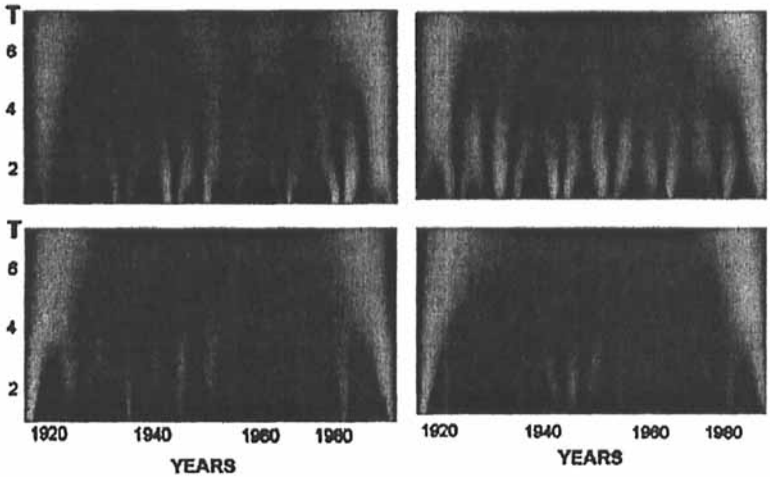


**Figure 2** The Wavelet diagramm for the magnetic moments.

where $B_r(\vartheta, \lambda)$ is the solar-surface magnetic field. We had only H$\alpha$ synoptic maps at our disposal, and we used +1 for positive and −1 for negative polarity. With $g_l^m$ and $h_l^m$ calculated, we can obtain the full synoptic magnetic maps at different heights above the photosphere with the analysis of structure and behaviour. The total number of harmonics in use was 9.

The field was assumed to be potential up to the source surface with a radius equal to $2.5R_0$, where $R_0$ is the radius of the solar photosphere. A more detailed description of the method is given in (Obridko and Shelting, 2000a; Ivanov-Kholodny *et al.*, 2000; Hoeksema and Scherrer, 1986). The coefficients are easily accessible through the INTERNET: *http://helios.izmiran.troitsk.ru/hellab/* Let us discuss the behavior of the harmonics with the zonal numbers $l$ = 0-9. The magnetic moments of multipoles $Mu_l(t)$ were calculated for every Carrington rotation

$$Mu_l(t) = \left(\sum(g_l^m g_l^m + h_l^m h_l^m)\right)^{1/2}. \tag{2}$$

Here, $g_l^m$ and $h_l^m$ are the spherical expansion coefficients, and the summation is performed for all $m$ from 0 up to $l$.

The Fourier spectrum of the magnetic moments calculated for the entire time interval under consideration is shown in Figure 1. The frequencies in inverse Carrington rotations are plotted on the abscissa axis. For example, the frequency 0.04 corresponds to 25 Carrington rotations (1.9 year). The spectrum of the even modes ($l$ = 2, 4, 6, 8) is shown on the right panel and the spectrum of the odd modes ($l$ = 1, 3, 5, 7, 9) on the left panel. It is evident that the QBO are allied to the global processes in the solar atmosphere and are only revealed in the lowest (global) modes ($l$ = 2, 3).

The figure was plotted using the whole database and illustrates the mean spectrum all over the observation interval. The contribution of QBO to the total spec-

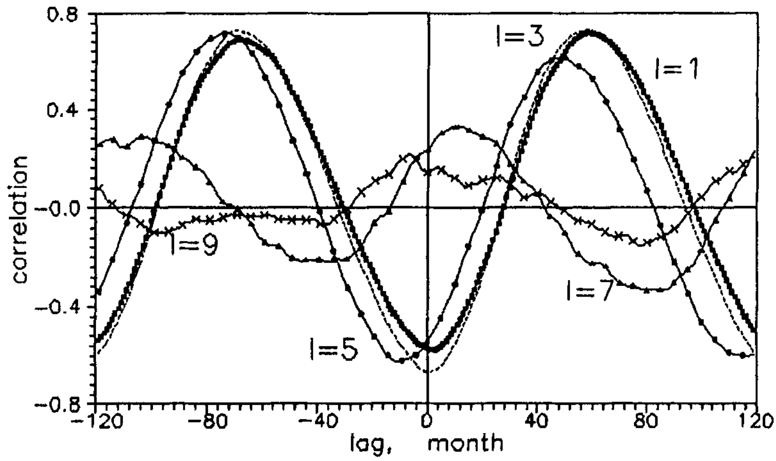


**Figure 3** The correlation of magnetic moments with Wolf numbers.

trum is likely to change with time. Therefore, we applied the WAVELET method of spectral-time analysis.

We used the basic function of 'Mexican hat'-type in WAVELET (Astafieva, 1996). The window was limited to a quarter of the total length of realization.

The WAVELET diagrams for the odd magnetic moments ($l$ = 1, 3, 5, 7) in the range of 0.9 to 7.5 years are shown in Figure 2. QBO are only observed in the lowest modes ($l$ = 1, 3) corresponding to the largest magnetic scale. They are especially well pronounced in the octupole variations ($l$ = 3). As should be expected, QBO manifest themselves in a different way at different times. They are best pronounced in the behavior of the dipole in cycle 18. The significance interval for the octupole is wider and involves the ascending branch and the phase of maximum of cycle 19. At $l \geq 5$, the QBO become weaker over the whole time interval under consideration.

It is interesting to note that QBO are also clearly seen in variations of the lowest even mode $l = 2$ (we do not show this plot here to save space). This mode determines the asymmetry of the global field parameters in the northern and southern hemispheres. This fact accounts for QBO observed in the asymmetry on the plots in (Obridko and Shelting, 2000b).

These results definitely imply the global nature of QBO. We should remember that the modes with QBO are just the modes that display a good correlation with the Wolf numbers at a shift of 5–6 years (see Figure 3).

## 4 QBO MANIFESTED IN THE ZONAL AND SECTORIAL MAGNETIC FIELD STRUCTURES

The energy indices of global magnetic fields are defined in (Shelting *et al.*, 1989; Obridko and Shelting, 1992). They can be briefly described as follows.

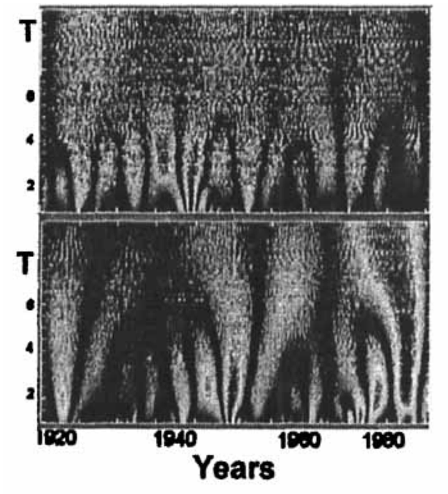


**Figure 4** The Wavelet analys of the $H_\alpha$ data.

The energy index $i(B_r)$ is the square of the radial magnetic field component averaged over a sphere of radius R from the center of the Sun:

$$i(B_r)|_R = \langle B_r^2 \rangle. \tag{3}$$

Using Eq. (1), we obtain for the source surface

$$i(B_r)|_{R_s} = \sum_{lm} (2l+1)\zeta^{2l+4}(g_{lm}^2 + h_{lm}^2), \tag{4}$$

where $\zeta = 0.4$.

We can also define the partial indices, namely, the zonal-even ZE ($m = 0$, $l = 2k$); zonal-odd ZO ($m = 0$, $l = 2k+1$); sectorial-even SE ($m = l = 2k$), and sectorial-odd SO ($m = l = 2k+1$) indices. Note that we introduced these indices to analyze direct magnetic measurements in our earlier work, where they characterized the mean energy of the magnetic field (or its particular structures) over the chosen surface.

The energy indices do not conserve their direct physical meaning when the H$\alpha$ magnetic data are used, but they are still useful in characterizing the relative importance and time variation of the zonal and sectorial structures (see Makarov *et al.*, 2000). Note that SO determines the importance of the most widespread 2- and 4- sector structures, and SE refers to unusual 3- and 5- sector structures or to a disbalance of the even sectors.

It should be mentioned that the zonal structure is a basic structure of the global magnetic field.

The WAVELET analysis of $H_\alpha$ magnetic data (Figure 4) show that QBO are best pronounced in the sectorial odd SO structures (upper panel) and are much weaker in the zonal odd ZO ones (lower panel). Short-term oscillations are clearly seen in SO, especially in the range of periods 1.6–2.0 and 3.0 years, and are present virtually all over the observation time. In ZO, the QBO are apparent much more seldom (around 1920, 1950 and 1985). As in the case of $Mu_3$ (see Figure 2), a gradual transfer of the oscillation energy to larger periods is observed both in SO and ZO. After cycle 18, the contribution of short-term variations weakens and grows again at the beginning of cycle 21.

## 5 QBO OF THE EFFECTIVE DIPOLE

11-year oscillations are seen well in $Mu_1$ (see Figure 2). $Mu_1$ is the magnetic dipole moment, which is the largest scale multipole in the expansion of the global field. Remember that $Mu_1$ can be divided into two components with different space–time parameters. For the sake of simplicity, they will be referred to as 'vertical' $D_v$ (with the axis parallel to the solar rotation axis) and 'horizontal' $D_h$ (with the axis in the plane of the equator) dipoles

$$D_v = g_1^0,$$
$$D_h = (g_1^1 g_1^1 + h_1^1 h_1^1)^{1/2}. \qquad (5)$$

$D_v$ is mainly determined by the basic zonal structure of the global field and is maximal at the minimum of the Wolf number cycle. $D_h$ is mainly connected with the two-sector structure, which is present in all phases of the solar cycle (Makarov *et al.*, 2000). One can see from WAVELET analysis (we do not show this plot here to save space), that the behavior of QBO in the vertical and horizontal dipoles is virtually the same as in ZO and SO, respectively.

Quasi-biennial oscillations are permanently present in SO and $D_h$ and are better pronounced for a clearer sector structure.

## 6 CONCLUSIONS

Thus, we arrived at the following conclusions:

1. QBO are mainly detected in variations of the largest scale structure of the global magnetic field.
2. QBO are mainly observed in variations of the sector structure of the global magnetic field
3. The importance of QBO changes with time and was maximal in the middle of the 20th century.
4. QBO are likely to be propagating features and to originate below the formation level of the 2- and 4-sector structures.

*Acknowledgments*

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