Astronomy Reports, Vol. 45, No. 12, 2001, pp. 1012–1017. Translated from Astronomicheskiĭ Zhurnal, Vol. 78, No. 12, 2001, pp. 1146–1152.
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Quasi-Biennial Oscillations of the Global Solar Magnetic Field

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Received March 16, 2001

Abstract—Quasi-biennial oscillations (QBOs) can clearly be distinguished in uniform series of data on the solar magnetic-field polarity derived from Hα observations in 1915–1999. These have been proven to represent oscillations of the global magnetic field of the Sun. This is verified by spectral analyses executed using various methods: the QBOs are clearly visible in low harmonics ($l = 1$–3), but abruptly disappear for $l = 4$ and higher. First and foremost, the QBOs are displayed in variations of the sector structure of the large-scale magnetic field, demonstrating that they correspond to variations of the horizontal multipoles.

1. INTRODUCTION

The current paper continues our study of the Sun's large-scale magnetic fields and their behavior over an extended time interval (1915–1999). The characteristics of the large-scale magnetic field have been derived from Hα observations using an original method [1–5]. We will consider in detail one specific property of the large-scale field, namely quasi-periodic two to three-year oscillations. These oscillations have been named the "quasi-biennial oscillations" (QBOs), and we adopt this term here.

QBOs have been detected in the solar atmosphere in numerous studies based on analyses of various solar signals and indices, and many papers have been devoted to this phenomenon. This oscillation mode has been detected in solar-activity variations in the polar zone [6, 7], features of the large-scale magnetic fields [8], dynamics of sunspot indices [9], and geomagnetic activity [10, 11]. We note also the detection of QBOs in the magnetic field of the Sun as a star [12], the solar neutrino flux [13–15], displacements of magnetic neutral lines [16], in the Earth's stratosphere [17] (though it is not clear if these are related to the solar QBOs), in the total flux of the solar radiation [18], and in the solar wind and heliospheric magnetic fields [19].

In general, the QBOs do not exhibit any stable harmonic oscillations. Their period has been found to vary strongly from 1.5 to 3 yrs in a number of observations. It is possible that the QBOs correspond to a sequence of impulses with a frequency of one pulse approximately every two years.

2. QBOs IN SECTOR STRUCTURES

We have shown in our previous works [4, 5] concerning two- and four-sector structures that QBOs are manifest in four-sector structures, especially near phases 0.1, 0.35, 0.7, and 0.9 of the cycle, when the amplitude of the four-sector structure exceeds that of the two-sector structure; i.e., when the four-sector structure becomes quite important. It is difficult to know whether these maxima are associated with these points in the cycle or if they exhibit quasi-periodic fluctuations with a period of two to three years. Since there are four reference points and phases of maximum and minimum in each cycle, changes in the activity at these times could be interpreted as quasi-biennial oscillations. On the other hand, it is possible that precisely these two to three-yr fluctuations stimulate the abrupt changes in solar activity that we identify as the reference points of the cycle.

The most ordered structure with a quasi-period of two to three yrs is the difference between the periods of the two-sector and four-sector structures (T2–T4) and its spectrum at all latitudes (see Fig. 5 in [5]). Such oscillations in T2–T4 are much more significant than the 11-year periodicity. Their behavior varies slightly with time, and is virtually independent of the phase of the 11-year cycle. The latitude dependence is weak, probably indicating that they occur at a considerable depth. Apparently, the period of the 11-year oscillations is an eigenperiod for the regions in which the global magnetic field is generated, and these oscillations are in phase at the two levels where the two-sector and four-sector structures originate. Therefore, subtraction weakens both modes at this frequency considerably. At the same time, the QBOs are much more weakly phased. This may simply be due to their lower period or may have a more global physical nature—that these oscillations are external to both levels and there is some phase delay due to propagation between the levels. Since the oscillations are out of phase, they are naturally attenuated much more weakly.

Here, we study biennial oscillations of the solar magnetic field in order to clarify their dependence on characteristic scales and structures. In Section 3, we calculate multipolar magnetic moments of various orders. The QBOs prove to be characteristic of the lowest harmonics; that is, they are global. In Section 4, we organize the data differently in order to study the zonal and sector structures separately. QBOs are more typical for sector than for zonal structures. In Section 5, we analyze oscillations of the magnetic moments of the polar and equatorial magnetic dipoles. The manifestations of QBOs in the polar and equatorial dipoles are essentially the same as those in the zonal and sector structures, respectively.

3. QBOs IN VARIATIONS OF THE MAGNETIC MOMENTS OF THE LARGE-SCALE MAGNETIC FIELDS

The intensities of various modes of the large-scale magnetic field and of polar and equatorial magnetic-field drifts have been studied using synoptic Hα maps of the solar magnetic field constructed for 1915–1999 using the technique of [1–3]. In order to compare the magnetic Hα maps with magnetograph measurements made at the Stanford Observatory, the synoptic maps were expanded in spherical harmonics, with the magnetic-field polarity being +1 G or −1 G [20, 21].

In a potential approximation expanding in spherical harmonics, we can express the solar magnetic field as a function of latitude θ, longitude φ, and the distance r from the center of the Sun:

$$B_r = \sum P_n^m(\cos\vartheta)(g_{nm}\cos m\varphi + h_{nm}\sin m\varphi) \tag{1}$$
$$\times\,((n+1)(R_O/R)^{n+1} - n(R/R_s)^{n-1}c_n),$$

$$B_\vartheta = -\sum \frac{\partial P_n^m(\cos\vartheta)}{\partial\vartheta}(g_{nm}\cos m\varphi + h_{nm}\sin m\varphi) \tag{2}$$
$$\times\,((R_O/R)^{n+2} + (R/R_s)^{n-1}c_n),$$

$$B_\varphi = -\sum \frac{m}{\sin\vartheta}P_n^m(\cos\vartheta)$$
$$\times\,(h_{nm}\cos m\varphi - g_{nm}\sin m\varphi) \tag{3}$$
$$\times\,((R_O/R)^{n+2} + (R/R_s)^{n-1}c_n).$$

Here, $0 \le m \le n < N$ (we adopted $N = 9$), $c_n = -(R_O/R_s)^{n+2}$, P_n^m are Legendre polynomials, and g_{nm} and h_{nm} are the spherical-harmonic coefficients determined by the initial data. For the synoptic Hα maps, we took only the sign of the magnetic field, +1 G or −1 G for positive and negative fields, respectively. The expansion coefficients g_{nm} and h_{nm} provide all the necessary information to reconstruct the synoptic map and analyze the magnetic-field distribution.

We assume that the field remains potential up to the source surface, whose radius is $2.5R_0$, where R_0 is the radius of the solar photosphere. The technique is described in detail in [4, 20, 21]. The coefficients calculated at the Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation are available on the internet at the address http://helios.izmiran.rssi.ru/hellab/default.htm.

Let us consider the temporal behavior of harmonics with zonal numbers l varying from one to nine. We calculate the multipolar magnetic moments for each Carrington period via the formula

$$Mu_l(t) = \left(\sum_m \left(g_{nm}^2 + h_{nm}^2\right)\right)^{1/2}, \tag{4}$$

with the summation being performed over all m from 0 to l.

Figure 1 shows the Fourier spectrum of the magnetic moments calculated for the entire time interval. The frequency is in reciprocal years. The left half presents even harmonics ($l = 2, 4, 6, 8$), and the right half, odd harmonics ($l = 1, 3, 5, 7, 9$). We can see that the QBOs correspond to the processes in the solar atmosphere with the largest spatial scales, which are manifest only in low (global) harmonics ($l = 1, 2, 3$).

Figure 1 was constructed using the entire dataset and shows the average spectrum over the entire time covered by the observations. At the same time, it seems reasonable to suppose that the contribution of the QBOs to the total spectrum could be different for different time periods. Therefore, we used the wavelet and swan spectral methods to improve the temporal resolution.

We have used a "mexican hat" convolution function when applying the wavelet program [22]. The limiting window did not exceed a quarter of the realization length. The swan spectral analysis method [23] uses a Fourier expansion in moving intervals. The length of the moving interval was also a quarter of the realization length.

Figures 2a–2d present wavelet diagrams for the odd magnetic moments ($l = 1, 3, 5, 7$). We performed the calculations of periods in the range from 0.9 to 7.5 yrs. The periods of oscillations are plotted along the vertical axis in Fig. 2. QBOs with periods of about two years are clearly pronounced only in the first two moments ($l = 1$, 3), corresponding to the largest scales of the magnetic field, and are most clearly seen in the octupole moment. As expected, the QBOs are manifest differently at different times. They

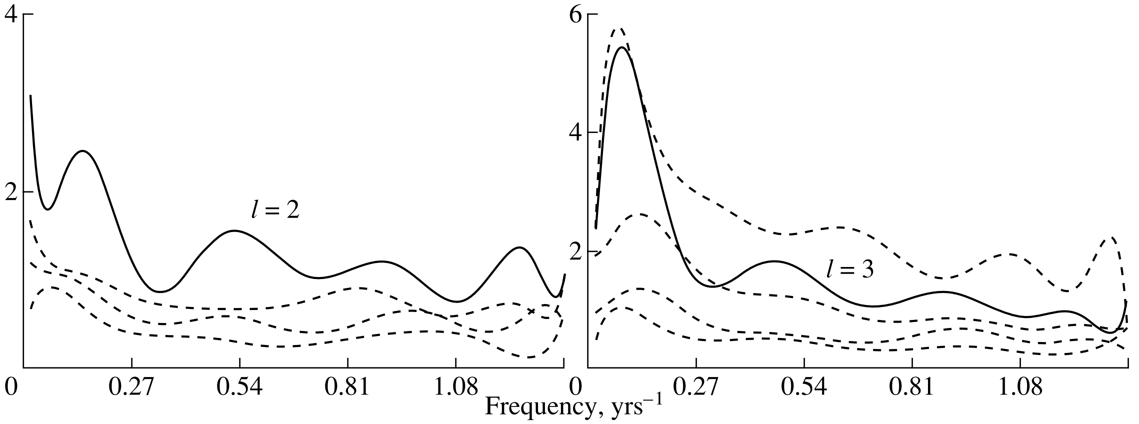

Fig. 1. Fourier spectra of the magnetic moments for the entire time interval under study. The frequencies in reciprocal Carrington periods are plotted along the horizontal axis and the spectral amplitudes along the vertical axis. The left half shows the spectra for even harmonics ($I = 2, 4, 6, 8$), and the right half, spectra for odd harmonics ($I = 1, 3, 5, 7, 9$).

are most intense for the dipole moment in the 18th cycle; in the octupole, this interval is broadened and encompasses the rising portion and maximum of the 19th cycle. Starting with $l = 5$, the spectrum for this period interval is abruptly attenuated during the entire time interval considered. Figures 3a and 3c present swan diagrams for two odd magnetic moments; the frequency is plotted along the horizontal axis. A horizontal strip at a frequency of 0.6 (i.e., a period of ≈ 1.7 yrs) can clearly be seen. The QBOs are pronounced in Fig. 3a ($l = 3$), while the spectrum for these periods is attenuated in Fig. 3c ($l = 1$). We can see that the QBOs display fine structure, demonstrating a set of oscillations with periods from two to three yrs, which evolve in different ways in time. In particular, energy was gradually transferred to lower frequencies, and there was a brief disappearance of the QBOs in the early 1960s.

It is interesting that the QBOs are also pronounced in the low even harmonic $l = 2$ (plot not shown), which determines the mutual asymmetry of the global field in the northern and southern hemispheres. This is consistent with the fact that the QBOs are clearly seen in the total Fourier spectrum in both even and odd low harmonics.

These results definitively demonstrate that the two-year oscillations have a global character. Here, we note that it was shown in [24] that precisely the harmonics displaying QBOs are correlated with the Wolf number with a delay of five to six yrs; such delays are typical for the global fields.

4. RELATIVE CONTRIBUTIONS OF ZONAL AND SECTOR MAGNETIC-FIELD STRUCTURES TO QBOs

Energy indices for the global magnetic field were introduced in [25, 26]. The meaning of these indices is the following. Let the square of the radial component of the magnetic field averaged over some spherical surface with radius R from the center of the Sun be the energy index $i(B_r)$:

$$i(B_r)|_R = \langle B_r^2 \rangle. \qquad (5)$$

Using (1), we obtain for the source surface

$$i(B_r)|_{R_s} = \sum_{lm} (2l+1)\, \zeta^{2l+4} \left(g_{lm}^2 + h_{lm}^2\right), \qquad (6)$$

where $\zeta = 0.4$.

We can also introduce partial indices, namely: the zonal-even index ZE [in this case, formula (4) contains only terms with $m = 0$ and even l]; zonal-odd index ZO ($m = 0$, $l = 2k + 1$); sector-even index SE ($m = l = 2k$); and sector-odd index SO ($m = l = 2k + 1$). Note that these indices were introduced in order to analyze direct measurements of the magnetic field and represent the average energy of the magnetic field or some of its components on a selected surface.

When using magnetic fields reconstructed from Hα measurements, these indices no longer have a direct physical meaning. However, they undoubtedly remain helpful, since they characterize the relative contributions and cycle phase variations of the zonal and sector structures [24]. Note that the SO index describes the contribution of the most common two-sector structures and other structures with $2m$ sectors, where m is odd. The SE index describes the contribution of the four-sector structures and other structures with $2m$ sectors, where m is even. It was shown in [24] that the zonal structure is most important for the global magnetic field.

The spectra calculated from the Hα data using the wavelet (Figs. 2e, 2f) and swan (Fig. 3) programs show that the QBOs are manifest most clearly in the odd sector SO structures (Fig. 3b) and much

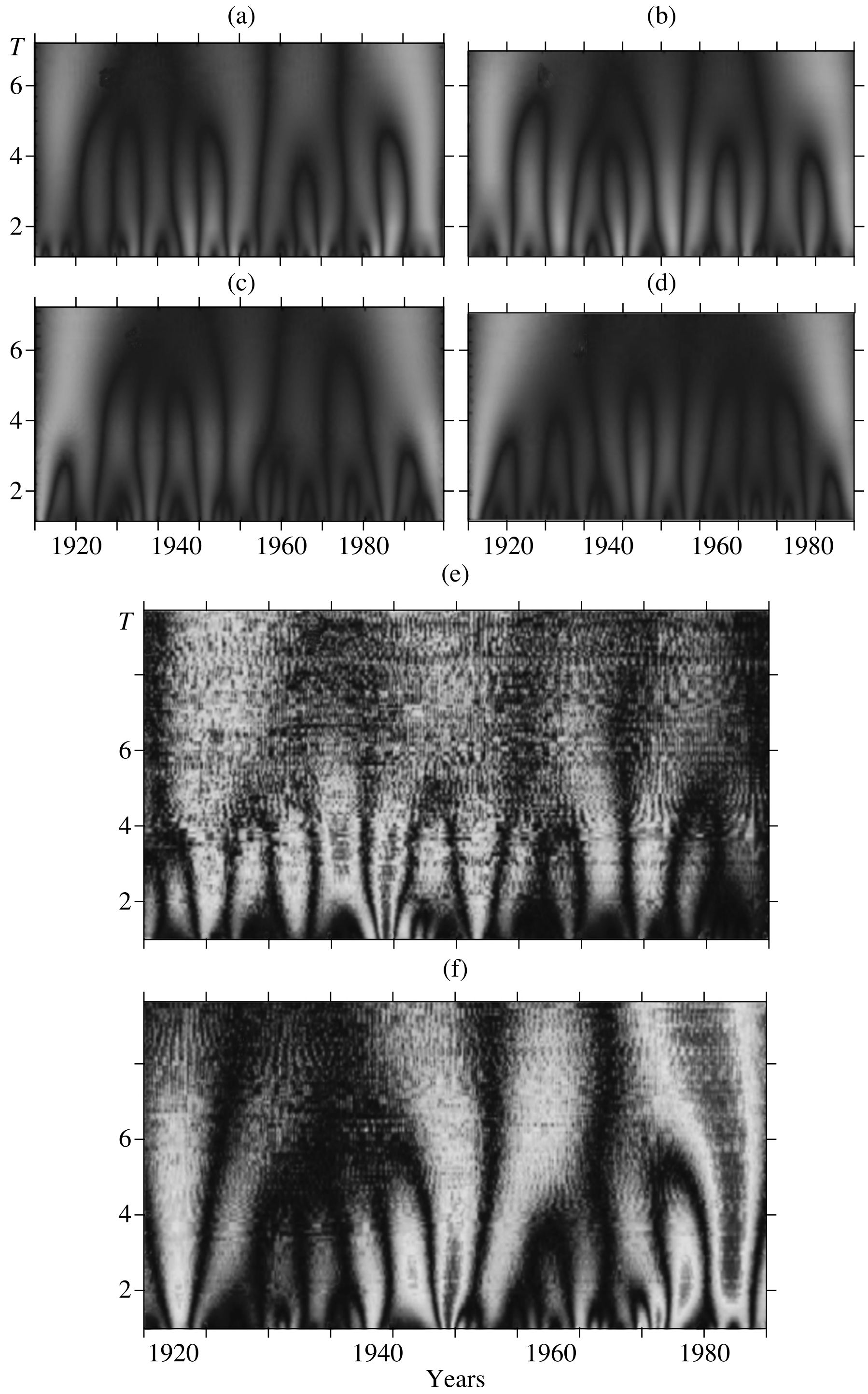

Fig. 2. Wavelet diagrams for the odd magnetic moments (a) $l = 1$, (b) 3, (c) 5, and (d) 7 with periods in the range from 0.9 to 7.5 yrs, and for the (e) odd sector structures and (f) odd zonal structures.

more weakly in the odd zonal ZO structures (Fig. 3d). The SO structures clearly display short-period oscillations with maxima at 1.6–2.0 and 3.0 yrs, which are present during virtually the entire time interval. The ZO structures display QBOs much more seldom (near 1920, 1950, and 1985). Similar to the behavior of the magnetic moments (Fig. 2), there is a gradual transfer of the energy of oscillations in SO and ZO structures to longer periods. This is especially pronounced in Fig. 2 for $l = 3$. After the end of

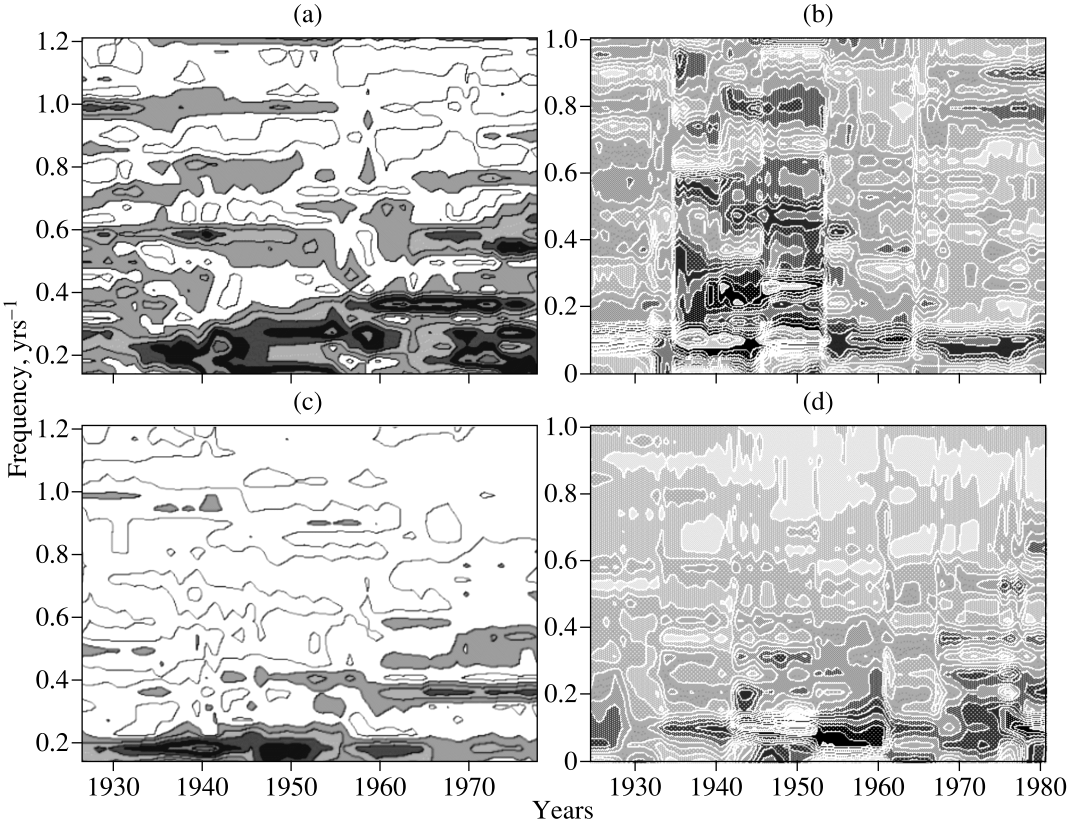

Fig. 3. Swan diagrams for the two odd magnetic moments (a) $I = 3$ and (c) $I = 1$, (b) odd sector structures SO, and (d) odd zonal structures ZO. The entire time interval in years is plotted on the horizontal axis and the periods in fractions of a year are plotted on the vertical axis.

the 18th cycle, the energy of short-period oscillations decreases, but increases again at the beginning of the 21st cycle.

We have compared the QBO for all types of indices derived from direct measurements of the magnetic field (the Stanford Observatory data) and from Hα data. A detailed description of this comparison is presented in [24], with an analysis of the SO indices being of particular interest. While, in the Stanford data, QBOs in the SO index are visible only near maxima of the cycles of local fields, in the Hα data they can clearly be seen during the entire interval considered. Since the contribution of local fields is weakened in the Hα data in comparison with the direct magnetic-field measurements, this clear expression of the QBOs provides evidence that these oscillations have a global character.

5. QBOs OF THE EFFECTIVE DIPOLE

Figure 2 shows that the 11-year oscillations dominate in Mu_1, which is the largest-scale component in the magnetic-moment expansion of the global magnetic field. However, note that Mu_1 contains two components with different spatial-temporal behaviors: we shall call these the magnetic moments of the polar D_v and equatorial D_h dipoles:

$$D_v = g_{10}, \tag{7}$$

$$D_h = \left(g_{11}^2 + h_{11}^2\right)^{1/2}. \tag{8}$$

D_v is predominantly determined by the main zonal component of the global field and reaches its maximum at the Wolf number minimum. D_h is associated with the two-sector structure, which is always present at every phase of the solar cycle [24]. The wavelet and swan diagrams obtained show that the QBOs in the vertical and horizontal dipoles are manifest similarly to those in the ZO and SO indices, respectively.

QBOs are continually present in the SO and D_h oscillations; i.e., they are associated with variations of the prominence of the two-sector structure.

6. CONCLUSIONS

We have arrived at the following main conclusions.

(1) First and foremost, the QBOs are manifest in oscillations of the very first harmonics of the global

magnetic field. In variations of the higher harmonics corresponding to medium-scale fields (down to the scales of active regions), QBOs are weakly expressed. The indices derived from the Stanford data (i.e., taking into account the field strength) do not display QBOs at cycle minima. At the same time, data constructed from Hα maps (i.e., mainly taking into account the field structure but not its strength) show comparable QBOs during the entire interval under study.

(2) QBOs are mainly displayed in variations of the sector structure of the large-scale magnetic field. Thus, the QBOs primarily represent variations of the equatorial dipole (and probably to a lesser extent of the quadrupole). Therefore, they are clearly seen in the large-scale magnetic fields and the locations of active longitudes [8], long-term dynamics of sunspot indices [9], geomagnetic activity [10, 11], displacement of magnetic neutral lines [16], and the heliospheric magnetic fields [19].

(3) The intensity of the QBOs varies with time and was maximum in the middle of the 20th century. The solar rotation reached its minimum precisely at that time [4, 5, 27]. It remains unclear if there is a relationship between these two phenomena.

ACKNOWLEDGMENT

This work was supported by the Russian Foundation for Basic Research (project no. 99-02-18346).

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Translated by V. Badin