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Medium-Term Oscillations of the Solar Activity

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Abstract.

Besides the well-known 11-year cycle, longer and shorter characteristic periods can be isolated in variations of the parameters of helio-geophysical activity. In geomagnetic variations, one can also isolate oscillations with characteristic periods of 5-6 years (QSO) and 2-3 years (QBO). Periods of ~36 and ~60 years were revealed in geomagnetic activity variations and a ~60-year periodicity, in correlation between the pressure in the lower atmosphere and the solar activity.We have considered 5-6-year periodicities observed in variations of the sunspot numbers and the intensity of the dipole component of the solar magnetic field. Comparison with different magnetic dynamo models allowed us to conjecture the origin of these oscillations. As a result of the study, we conclude that the 5-6-year activity variations are related to the processes of nonlinear saturation of the dynamo in the solar interior. Quasi-biennial oscillations are actually separate pulses related little to each other. Therefore, the methods of the spectral analysis do not reveal them over large time intervals. They are a direct product of local fields, are generated in near-surface layers, and are reliably recorded only in the epochs of high solar activity.

Introduction

The main cycle of activity with the magnetic-field sign variations taken into account is ~20 years. Accordingly, the SSN variations determined by the energy of the magnetic field (i.e., its square intensity) have a half period (about 10 years). These cycles are determined by a large-scale dynamo process. The equations describing the dynamo process have eigenvalues, which determine this main cycle.

As concerns other periodicities found in the solar cycle, the situation is much more complicated. The difficulty is that the wavelet analysis of sunspot data [Frick et al., 1996] does not recognize 7-year (and 2-year) fluctuations. [Obridko et al., 2006] tried to overcome this difficulty by considering the presence of a subcritical dynamo with a period of about 7 years between the modes. This regime corresponds to a strong toroidal field emerging from the lower part of the convection zone.

In this brief review, we will focus on secondary variations. These are short-term (1-4 years) quasi-biennial oscillations (QBO), medium-term (4-8 years) quasi-sexennial oscillations (QSO), and long-term variations (over 50 years). The origin of these variations is not completely clear. They are apparently associated with the turbulent decay of large-scale magnetic structures, nonlinearity of the dynamo process, and fluctuations of parameters. We do not intend to provide here a comprehensive review of the data available. Rather we are going to outline some possibilities and difficulties of explaining the generation of such variations on the Sun.

A special note (which is appropriate at a geophysical conference) is that many variation periods of the solar activity were first established in variations of geophysical parameters. In this sense, the Earth turns out to be in itself an observational instrument for studying solar activity.

Quasi-biennial oscillations (QBO)

Quasi-biennial oscillations are known almost as widely as the 11-year cycle. Some authors considered them even a more fundamental phenomenon than the 11-year cycle [*Ivanov-Kholodny et al*., 2006*; Ivanov-Kholodny and Chertoprud*, 2009]. There is a vast bibliography devoted to QBO. We will focus here only on a few milestones in the history of the QBO studies.

Quasi-biennial oscillations were first reported by *Reed* [1960] as 26-month oscillations in the system of tropical atmospheric winds. All works published during seven years after that concerned QBO only in the Earth's atmosphere (references can be found in [*Maeda*, 1967]). It was Maeda who first, in 1967, drew attention to the fact that QBOs were also observed in cosmic rays But, there is still no certainty that QBOs on the Sun and Earth are directly related [*Baldwin et al.*, 2001*; Petrick et al.*, 2012].

The next important step was taken in the works by Karin Labitzke and Van Loon [*Labitzke*, 1987; van *Loon and Labitzke*, 1988*; Labitzke and van Loon*, 1989]. They showed that there was a relationship between the polar stratospheric temperature in the northern winter and the solar cycle in the winters when equatorial 50 mb winds were blowing from the west: the fewer sunspots in such winters, the lower the temperature.

Only in the early 1990-ies is was suggested that similar quasi-biennial oscillations could also occur in the Sun [*Djurovic and Pâquet*, 1990*; Hoeksema*, 1991*; Obridko and Gaziev,* 1992].

In 1995, Elena Benevolenskaya published a very important work, which is sometimes mistakenly referred to as the first work on solar QBOs [*Benevolenskaya,* 1995]. In fact, the importance of this work is that she proposed interpretation of QBO as a manifestation of a double dynamo cycle. Later, *Benevolenskaya* [1998] formulated the concept of two spatially separated dynamos - at the base of the convection zone and immediately below the surface.

So, what do we know about QBO today?

Quasi-biennial oscillations are actually separate impulses poorly related to each other. They are a directly produced by local fields in the near-surface layers and are reliably recorded only during the periods of high solar activity.

Figure 1 shows by way of example the squared magnetic field on the photosphere surface averaged over a Carrington rotation as a function of time. One can see that the pulses do not form a quasi-periodic process; individual pulses are not phase-related. The spectral methods do not detect them over large time intervals because of the chaotic nature of the phase shifts.

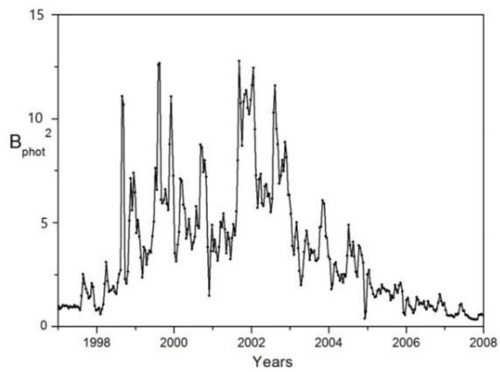

Fig.1. Squared magnetic field on the photosphere surface averaged over a Carrington rotation as a function of time.

To understand the origin of quasi-biennial oscillations, it is important to find out what scale of the large-scale field they are associated with. Such an analysis was performed in [*Obridko and Gaziev,* 1992; *Shelting and Obridko,* 2001; *Obridko and Shelting*, 2003; *Obridko et al*., 2006]. It turned out that QBOs are associated with structures that are even with respect to the equator. The amplitude of fluctuations in the range of the periods of 1.5-2.5 years was identified on the synoptic maps using the wavelet analysis [*Obridko et al.,* 2006] (see Figure 2).

The magnetic field pattern on the latitude-time diagram looks like a set of bands running from the equator to the poles. The width of the bands is approximately 2 years. The bands drift towards the poles. The duration of the drift of each band is also several years. One can clearly see enhancements in the vicinity of the solar maxima and weakening as the solar activity decreases.

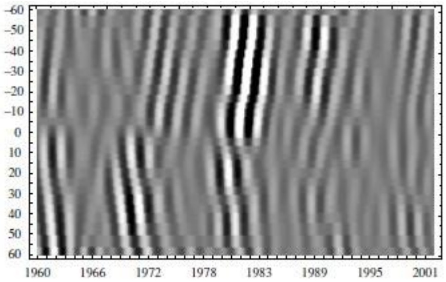

Fig. 2. Synoptic diagram of the amplitude of the magnetic field component even with respect to the equator.

When expanding the photospheric magnetic field into Legendre polynomials, we naturally see the even harmonics in the QBO spectrum best of all. There is also another particularity: the QBO are revealed mainly in the relatively low-order harmonics with l=2 and l=4. This is visible on the wavelet diagram (Fig. 6). In addition, one can clearly see these oscillations intensify at the cycle maxima (Figs.2 and 3). Since the 1980-ies, they have been gradually weakening in accordance with the general trend of decreasing solar activity.

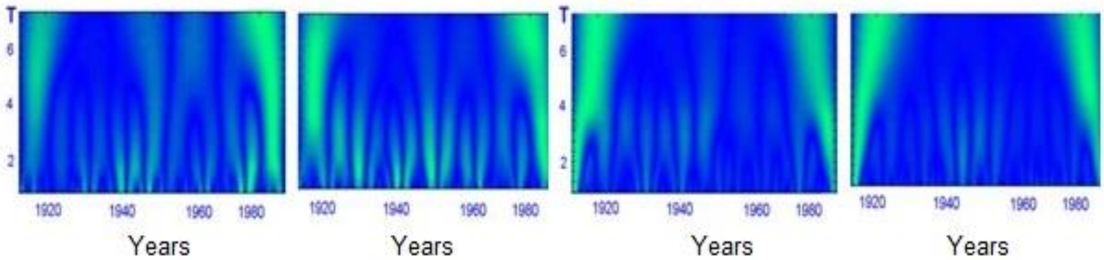

Fig.3. Wavelet diagram of the photospheric magnetic field in the range of 2-6 years. Shown are the harmonics with l=2,4,6,8.

Quasi-sexennial oscillations (QSO)

The analysis of the global magnetic field carried out in these papers, revealed the existence of quasi-sexennial oscillations, i.e., variations with a period of about half an 11-year cycle.

A smoothed butterfly diagram for the spectral band of 5.5-7.5 yr is shown in the Fig. 4 [*Obridko et al.,* 2006]. Note that the stripes that represent amplitude oscillations in this band are anti-symmetric relative to the equator, i.e., they form an odd system.

The existence of QSO was confirmed in a number of subsequent publications. Gavryuseva [2006] isolated this period in the differential rotation of the photospheric magnetic field and Den et al. [2020], in the rotation of the corona. Le Mouël, Lopes, and Courtillot [2019] analyzed the periodicities of sunspots, polar plumes, aa and Dst geomagnetic indices and showed that only the periods of 22, 11, and 5.5 years were present in all realizations.

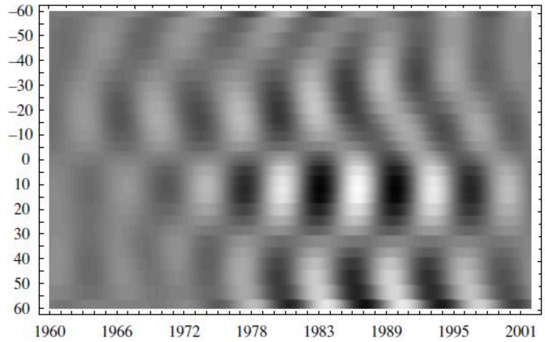

Fig. 4. Smoothed butterfly diagram for a spectral band (5.5-7.5 yr).

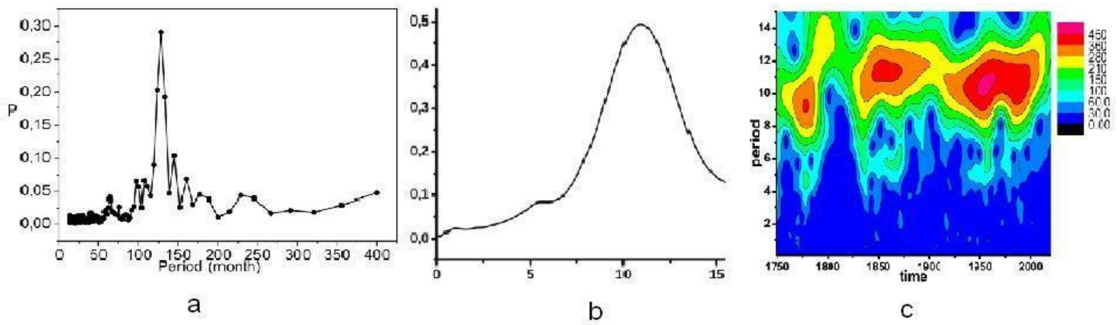

Fig. 5. (*a) Fourier spectrum for the monthly mean sunspot data for the time interval 1749–2019. P is the amplitudes of the Fourier harmonics normalized to the sum of their moduli. The harmonic of the maximal amplitude corresponds to the 25th harmonic, i.e. 126 months. The spectral resolution in the calculated spectrum is about five months. (b) Integral wavelet spectra for sunspot data. (c) The wavelet plane for the real part of the modulus of the sunspot wavelet coefficients (color version online).*

Figure 5 is a result of the spectral analysis of sunspot numbers (SSN) for the period from 1750 to 2021. Fig. 5a illustrates the spectral Fourier analysis. One can readily see QSO, while QBO are virtually absent. Figs. 5b and 5c illustrate the results of the wavelet transform. Here, the QSO are clearly visible, too. Besides that, one can see that oscillations in the range of 5-7 years disappear completely in the epochs of the Dalton and Gnevyshev secular minima, as well as at the present time.

Gleissberg cycle (80-60 years)

This variation was first isolated by Gleissberg in 1944 [*Gleissberg*, 1944, 1965]. The studies of the Gleissberg cycle have revealed variation periods of 55, 65, 58, 78.8, 83, 87, 95, 104, 130, and 150 years [*Kuklin*, 1976; *Silverman*, 1992; *Feynman and Fougere*, 1984; *Ogurtsov et al.*, 2002; *McCracken et al*., 2013; *Usoskin*, 2017]. Most likely, the resulting cycles have no strict periodicity. It is assumed that they are rather variations with a changing period that ranges from 50 to 160 years [*Ogurtsov* et al., 2002].

Because of a significant duration of this cycle, its study requires long series of data. Unfortunately, reliable series of direct solar observations of such duration are not available. Therefore, all studies dealing with the analysis of the Gleissberg cycle usually rely on geophysical data as mentioned above in the Introduction. *Ptitsyna and Demina* [2020] performed a reconstruction based on the statistics of polar lights at mid latitudes with allowance for the screening effect of the Earth's magnetic moment for 700 years (1000-1700). In [*Ptitsyna and Demina*, 2021], they used this 700-year series, as well as the reconstruction based on the content of radiocarbon 14C in tree rings for ~11350 years [Solanki et al., 2004]. The analysis has shown that the Gleissberg cycle consists of three components with the periods of 130-100, 100-80, and 60 years.

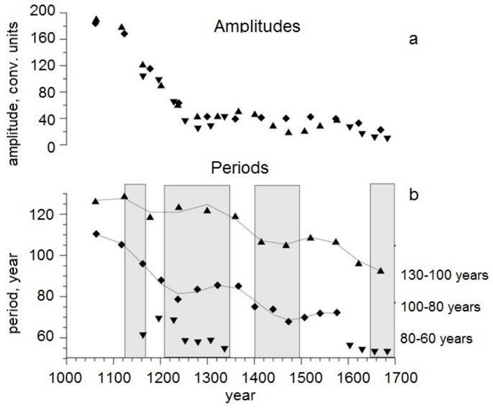

Fig.6. Variations in the amplitude and period of the Gleissberg cycle in 1000-1700. Symbols show the experimental values; the solid line is approximation by the sum of sinusoids. The grey areas correspond to the Oort, Wolf, Spörer, and Maunder Minima. (The figure was borrowed from [Ptitsyna and Demina, 2021], courtesy of the authors).

It should be noted that, like the QBO and QSO, the components of the Gleissberg cycle weaken and somewhat decrease in the epochs of the Grand Minima. The components with a period from 36 to 60 years are described on the basis of geophysical data in [Veretenenko and Ogurtsov, 2014; Veretenenko et al., 2020]. Quasi-periodic fluctuations with these periods are known to exist in geomagnetic activity. An approximately 60-year periodicity was discovered in the evolution of correlations between the pressure in the lower atmosphere and characteristics of solar activity. Similar periods are observed in the cyclonic activity.

2D dynamo model

Now, compare the results of the spectral analysis based on observational data with the data derived from the mean-field dynamo model. A preliminary analysis shows that QSO in the axial dipole can be reproduced in terms of different mean-field dynamo models, e.g. the 1D models proposed in [*Moss and Brandenburg*, 1991; *Moss et al.*, 2008] and the recent 2D model by *Pipin and Kosovichev* [2020]. We have found that the presence of the non-linear dynamo saturation effect is sufficient for the emergence of QSO, both in the parameters of the toroidal magnetic field and in the axial dipole. For our study, we need the parameters of both the axisymmetric and non-axisymmetric large-scale magnetic fields. For this reason, we use the simplified version of the non-axisymmetric dynamo model. The model simulates the dynamo process in a thin layer deep in the convection zone. The effect of magnetic buoyancy seeds the bipolar active region at a random position within the large-scale toroidal magnetic field. This effect accounts for the escape of magnetic energy from the dynamo region, as well. Magnetic buoyancy [*Kitchatinov and Pipin*, 1993] occurs at an arbitrary longitude, at a random time (correlation time of about 0.01 of the dynamo period), and in a randomly selected hemisphere [*Pipin and Kosovichev*, 2018].

To clarify the nature of QSO periodicity, we have followed the evolution of the magnetic field starting with a tiny seed magnetic field [*Sokoloff et al.*, 2020]. It is found out that the 11-year periodicity starts at the very beginning of the magnetic field evolution. Quasi-sexennial oscillations gain considerable power when the dynamo cycle becomes stationary as the magnetic energy reaches the nonlinear saturation state. This means that QSO can be considered a non-linear effect. Note that the non-linear saturation in the model is due to the magnetic buoyancy effect. The time evolution of the axial and equatorial dipoles is discussed. The latter looks like noise, while the time evolution of the axial dipole seems to be almost sinusoidal. Also, we have found out that the maximum power of the axial dipole QSO is observed at the rise and decline of the axial dipole cycle. This result of the dynamo-model agrees qualitatively with our observational findings. The integral wavelet spectra for the axial and equatorial dipole in our dynamo model are shown in Fig.7. However the QBO in model calculations are not pronounced, although they are seen in the observation data.

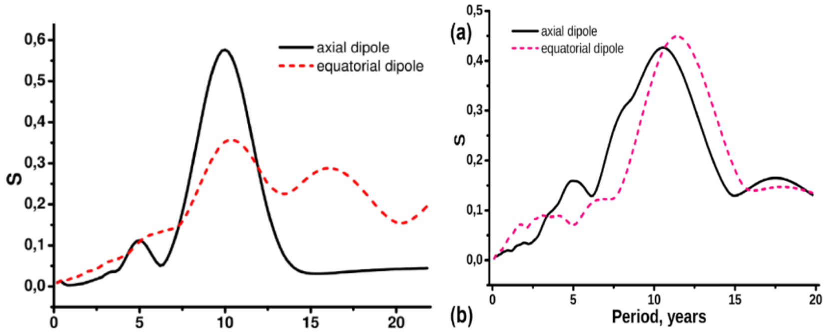

Fig. 7. Dynamo model: the integral wavelet spectra for the axial and equatorial dipole (left – model; right – observed.)

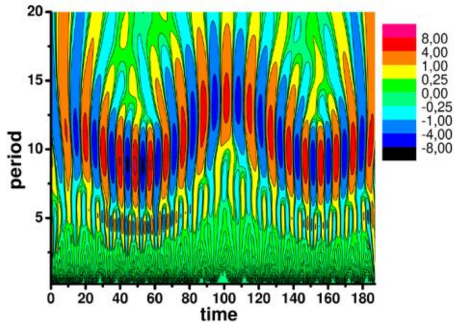

Fig. 8. 2D wavelet spectra for the model with a variable α effect.

Variations in the period of the axial dipole cycle and QSO in the dynamo model output are shown in Fig. 8. We see that a shift of the cycle period results in a corresponding shift of the QSO period.

The model shows that the period of the dipole cycle increases to about 15 years during the grand minimum. The corresponding QSO almost disappear during this period. The model shows similar behavior of the long-term evolution of QSO in the mean flux density of the toroidal magnetic field. Bearing in mind our mechanism for QSO, we suggest that the analysis of longer observational time series of the axial dipole may reveal saturation of the QSO power in the case of strong variations in the axial dipole cycle.

The dynamo model suggests that QSO reflect the nonlinear shape of the cycles of the activity parameters. The model results are reproduced for different types of nonlinearity.

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