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MEDIUM-TERM OSCILLATIONS OF THE SOLAR ACTIVITY

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Abstract. In addition to the well-known 11-year cycle, longer and shorter characteristic periods can be isolated in variations of the parameters of helio-geophysical activity. Periods of about 36 and 60 years were revealed in variations of the geomagnetic activity and an approximately 60-year periodicity, in the evolution of correlation between the pressure in the lower atmosphere and the solar activity. Similar periods are observed in the cyclonic activity. Such periods in the parameters of the solar activity are difficult to identify because of a limited database available; however, they are clearly visible in variations of the asymmetry of the sunspot activity in the northern and southern solar hemispheres. In geomagnetic variations, one can also isolate oscillations with the characteristic periods of 5-6 years (QSO) and 2-3 years (QBO). We have considered 5-6-year periodicities (about half the main cycle) observed in variations of the sunspot numbers and the intensity of the dipole component of the solar magnetic field. A comparison with different magnetic dynamo models allowed us to determine the possible origin of these oscillations. A similar result can be reproduced in a dynamo model with nonlinear parameter variations. In this case, the activity cycle turns out to be anharmonic and contains other periodicities in addition to the main one. 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 the near-surface layers, and are reliably recorded only in the epochs of high solar activity.

1. Introduction

Solar activity is a complex of many processes. Therefore, even a well-established periodicity itself does not tell us much about the physical mechanism. In particular, there is no doubt that the main periodicities on the Sun are the rotation period and the 11-year cycle. However, these periods can change over time both in duration and in phase.

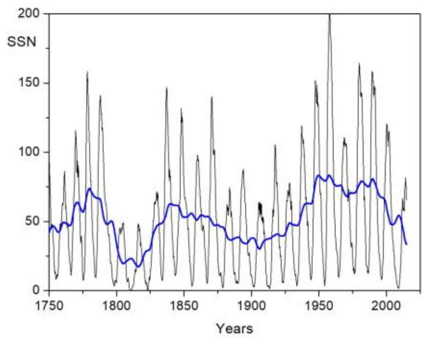

Figure 1. Monthly mean sunspot numbers SSN vs. time. The blue curve represents the smoothing with a 22-year window.

Solar activity is usually characterized by the so-called sunspot number (SSN). In fact, this is not the real number of spots on the solar disk, but a certain index calculated following a certain procedure. This procedure has been changed more than once, and the values have been revised. The version of the SSN index officially adopted today is available on the website of the Royal Observatory of Belgium http://sidc.oma.be/silso/datafiles.

Figure 1 represents the time dependence of the monthly mean sunspot numbers SSN. The blue curve shows smoothing by a 22-day window. One can see both the 11-year cycle and long-term variations. The grand minima were recorded during 1645-1710 (Maunder minimum, not shown in this figure), 1710-1830 (Dalton minimum), and a long-lasting decrease at the beginning of the XX century sometimes called the Gnevyshev grand minimum). There is some reason to believe that the next grand minimum (or several relatively low cycles) will be observed at the beginning of the XXI century.

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.

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.

2. Quasi-sixty-year variations

In this Section, we will briefly describe the results obtained by *Veretenenko and Ogurtsov* (2014) and *Veretenenko et al.* (2020).

Quasi-periodic fluctuations with periods of about 36 and 60 years are known to exist in geomagnetic activity. An approximately 60-year periodicity has been discovered in the evolution of correlations between the pressure in the lower atmosphere and characteristics of solar activity. Similar periods are observed in cyclonic activity.

In the epochs of a strong polar vortex, one can observe an enhancement of the arctic anticyclones and mid-latitude cyclones associated with an increase in GCR fluxes at the minima of the 11-year solar cycles. The results obtained indicate that the mechanism of the influence of solar activity and cosmic rays on the circulation of the lower atmosphere involves changes in the evolution of the stratospheric polar vortex.

The Northern Annular mode (NAM) in the stratosphere of the North hemisphere is the measure of the vortex. On the surface, this phenomenon manifests itself as the Arctic Oscillation (AO). The positive phase of AO is characterized by abnormally low pressure in the polar region and abnormally high pressure at subtropical and mid latitudes.

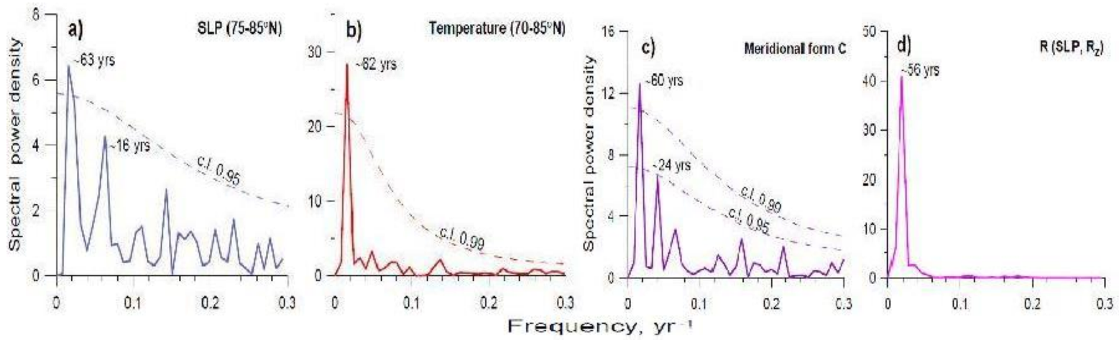

Figure 2. The Fourier spectra of the sea level pressure (a) and temperature (b) anomalies in the Arctic region, the frequency of occurrence of the C-type meridional circulation (c) and correlation coefficients *R(SLP,Rz)* between SLP at high latitudes (60-85N) and relative sunspot numbers (d). Confidence levels are calculated for a red noise with AR(1) coefficient a=0.3 (a), 0.65 (b) and 0.4 (c).

Figure 2 represents the Fourier spectra of sea level pressure and temperature, anomalies in the Arctic region, the occurrence rate of the C-type meridional circulation, and the correlation coefficients R(SLP, Rz) between SLP at high latitudes (60-85N) and relative sunspot numbers. The confidence levels are calculated for red noise with the AR(1) coefficient *a* equal to 0.3 (a), 0.65 (b), and 0.4 (c).

Long-term periods in the characteristics of solar activity are difficult to identify because of the limited set of data; however, they are clearly visible in the varying asymmetry of the sunspot production activity in the northern and southern solar hemispheres. Besides that, they are readily revealed in the characteristics of magnetic storms of different types, especially, in the occurrence rate of the storm gradual commencements, which are mainly determined by fluxes from solar coronal holes. Since the solar coronal holes are one of the indices characterizing the large-scale fields, the relationships obtained definitely indicate to generation of the large-scale dynamo. The possibility of simulating such generation processes is described below in Section 5.

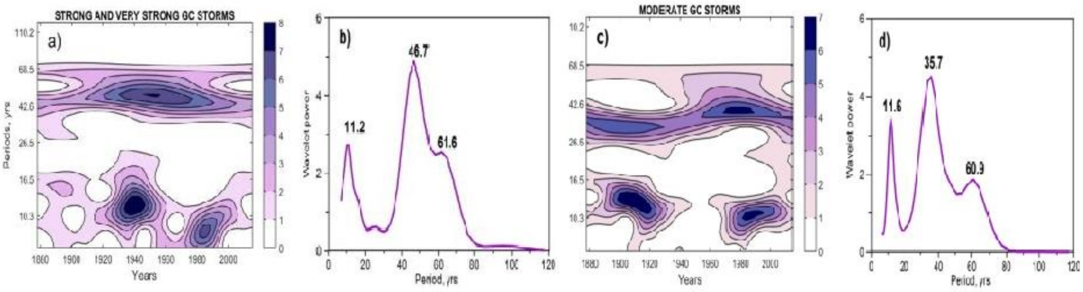

Figure 3. Local and global Morlet wavelet power spectra of annual occurrence frequencies for major (a, b) and moderate (c, d) magnetic storms with gradual commencements after the removal of polynomial trends. The spectra are normalized by variance.

3. 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. Suffice it to mention a fundamental review by *Bazilevskaya et al.* (2014), which contains about 170 references. We will focus here only on a few milestones in the history of the QBO studies.

3.1. The history of the discovery and study of QBO

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 He showed that atmospheric variations had a reflection in cosmic ray variations; however, in that work, he did not discuss the existence of QBOs on the Sun. Moreover, 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. During these winters, there were no major warmings in midwinter when the sunspot number was below 100. Such relationship is absent in the easterly phase of QBO. In this phase, the temperatures are usually higher than in the westerly phase, and significant warmings in midwinter occur regardless of the state of the solar cycle.

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 1991, a National Symposium on Quasi-Biennial Solar Variations (From the Core of the Sun to the Earth's Magnetosphere) was held in the USSR (Pushchino Observatory). Unfortunately, the full Proceedings of this symposium were never published. Only extended abstracts in English are available in the Solar Data Bulletin, February 1991.

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. The model of two dynamos was widely discussed subsequently, for example, in (Beaudoin et al., 2016; Yushkov et al., 2018, 2019) as the interaction of a mean-field dynamo at the tachocline level and a turbulent small-scale dynamo. The works by Benevolenskaya made a great impression. They were referred to hundreds of times and stimulated multiple attempts to detect QBO directly on the Sun.

3.2. 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 4 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.

The analysis of sunspot areas carried out by *Wang and Sheeley* (2003) also revealed periods ranging from 0.2 to 2.6 years with none of the periods prevailing.

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. This was shown by constructing long-term synoptic maps based on direct measurements of the Wilcox Solar Observatory, WSO (*Hoeksema*, 1991) and on a long series of reconstructed solar magnetic data (*Obridko and Gaziev*, 1992). 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 5).

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.

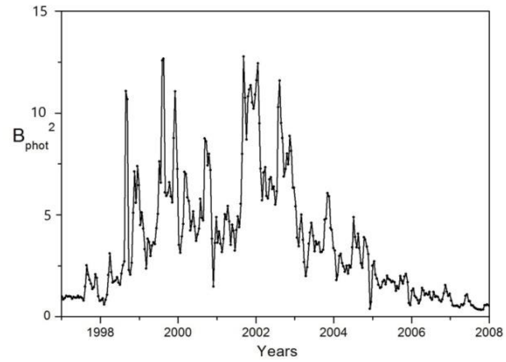

Figure 4. Squared magnetic field on the photosphere surface averaged over a Carrington rotation as a function of time.

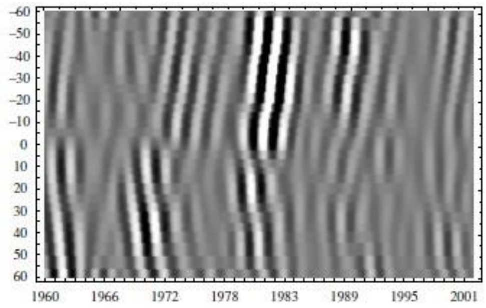

Figure 5. Synoptic diagram of the amplitude of the magnetic field component even with respect to the equator.

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. 5 and 6). Since the 1980-ies, they have been gradually weakening in accordance with the general trend of decreasing solar activity.

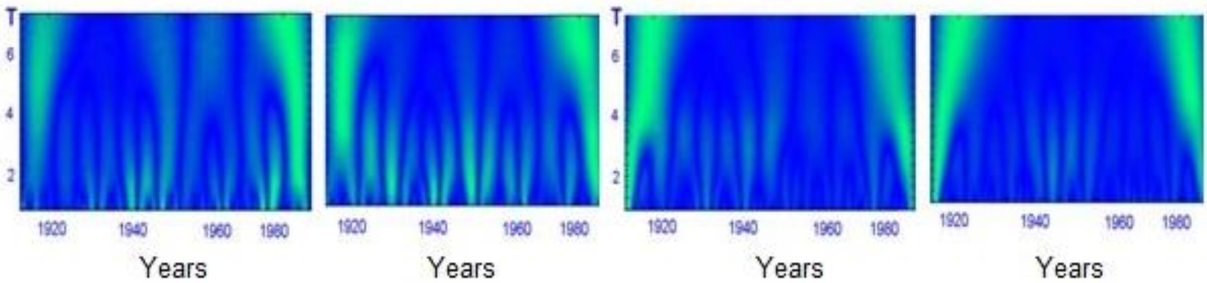

Figure 6. Wavelet diagram of the photospheric magnetic field in the range of 2-6 years. Shown are the harmonics with l=2, 4, 6, 8.

Besides that, *Wang and Sheeley* (2003) observed a periodicity in the range of 1-3 years in the photospheric parameters of the equatorial dipole. It had to be expected because the equatorial dipole with l=m=1 also forms an even structure relative to the equator.

Indeed, QBO are visible in the spectrum of the equatorial dipole (Fig. 7), while in the spectrum of the axial dipole, one can see oscillations of different type (QSO).

4. 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. 8 (*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.

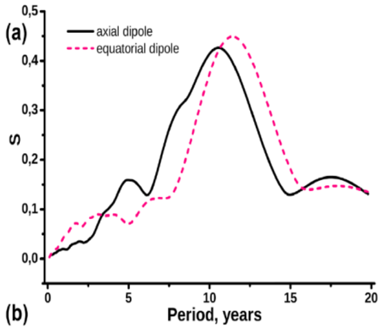

Figure 7. Wavelet spectrum of the axial (l=1, m=0) and equatorial (l=1, m=1) dipoles.

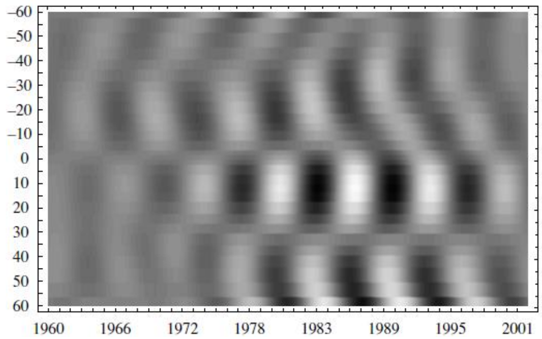

Figure 8. Smoothed butterfly diagram for a spectral band (5.5-7.5 yr).

The difficulty is that the wavelet analysis of sunspot data (*Frick et al.*, 1997) 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.

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 *Deng et al.* (2020), in the rotation of the corona. *Le Mouël et al.* (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.

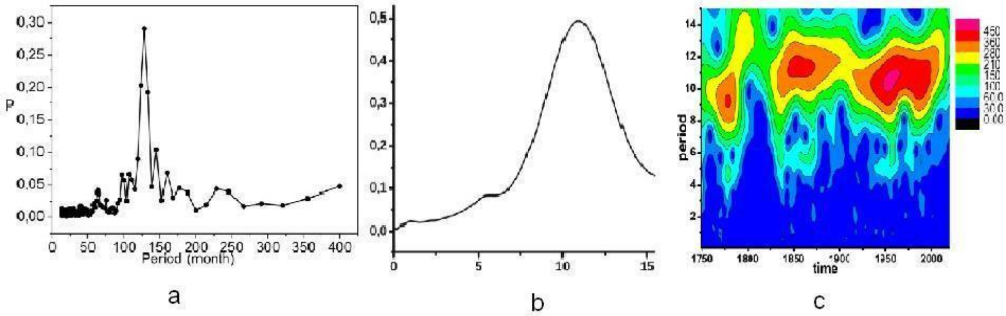

Figure 9. (a) Fourier spectrum for the monthly mean sunspot data for the time interval 1749–2019. P is the amplitudes of the Fourier harmonics normalized to the sum of their moduli. The harmonic of the maximal amplitude corresponds to the 25th harmonic, i.e. 126 months. The spectral resolution in the 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 9 is a result of the spectral analysis of sunspot numbers (SSN) for the period from 1750 to 2021. Fig. 9a illustrates the spectral Fourier analysis. One can readily see QSO, while QBO are virtually absent. Figs. 9b and 9c 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 in the present time.

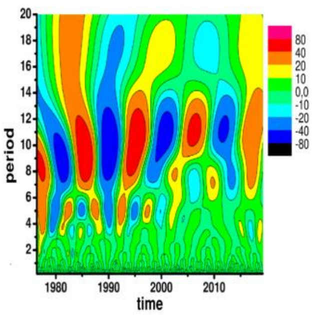

Figure 10. Wavelet plane for the real part of the modulus of the axial dipole wavelet coefficients based on WSO data.

The same is seen from the wavelet transform for the axial dipole based on WSO data for 1976-2020 represented in Fig. 10 (the equatorial dipole is not given here, because it does not show QSO). Since the late 1990-ies, the overall activity has been decreasing and, accordingly, QSOs disappear.

5. 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 by *Brandenburg et al.* (1991) and *Moss et al.* (2008) and the recent 2D model proposed 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 within 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. 11 (compare with experimental graphs in the Fig. 7).

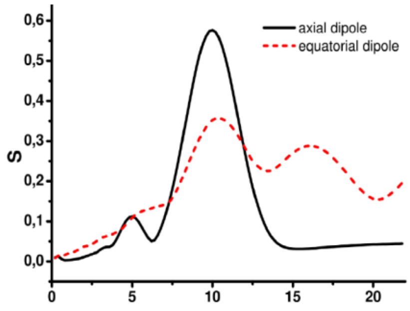

Figure 11. Dynamo model: the integral wavelet spectra for the axial (solid line) and equatorial dipole (dotted lines).

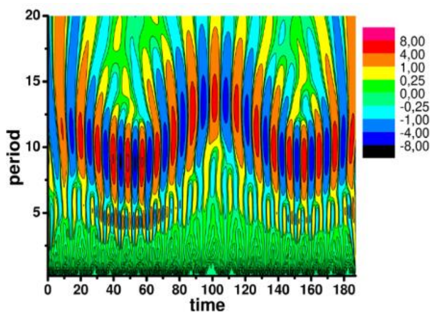

Figure 12. 2D wavelet spectra for the model with a variable α effect.

Variations in the period of the axial dipole cycle and QSO in the dynamo model output are shown in Fig. 12. We see that a shift of the cycle period results in a corresponding shift of the QSO period.

This agrees qualitatively with the results shown in Figs. 9c and 10 above. 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. The anharmonic form of the cycles of the toroidal field was discussed earlier in the context of variation mechanisms in stellar cycles (e.g., *Baliunas et al.*, 2006). The nonlinear dynamo is generally used to explain the parity mode interactions. These mechanisms have a long relaxation time, in contrast to the B^2 anharmonicity effect. In the fast rotation mode, the distortion of the cycles becomes comparable to the amplitude of the cycle (*Pipin*, 2021); therefore the signals associated with magnetic energy have twice the frequency relative to the main period.

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