"Physics of Auroral Phenomena", Proc. XXV Annual Seminar, Apatity, pp.143-146, 2002

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QUASI-BIENNIAL VARIATIONS OF THE SOLAR ACTIVITY DURING THE 11-YEAR CYCLE AND THEIR DISPLAY IN THE VARIATIONS OF THE TEMPERATURE OF THE MIDDLE ATMOSPHERE

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Abstract. The Quasi-Biennial Oscillations (QBO) are known to be an essential property of different geophysical processes. It is shown that they are the main component of the solar activity (SA) variations as well. Their structure and character are analyzed. It is shown that the similar wave trains of the quasi-biennial variations are main property of the fine structure of the 11-year SA cycle. In each case these variations are a superposition of consecutive, nearly equal extinction wave trains appearing regularly with 10 – 11 year interval. The main wave train begins shortly before the end of the previous cycle. Its two front maxims are amplified by the interference with the end of the previous wave train. This leads to the well-known bimodal structure of the 11-year cycles. The deep and broad minimum of the following wave train suppresses the current cycle determining the exact moment of its minimum and of the following cycle beginning. The wave period is about 38 months at epoch of SA maximum linearly diminishing to 21 months toward the cycle end. The separate wave trains are well presented by the analytical Airy functions. The origin of the outlined structure suggests its connection with the dynamical processes in the deeper layers of the Sun and presumably in its convection zone.

Introduction

The main property of the solar activity (SA) is the stable 11-year cycle. There is no precise periodicity due to variations of the individual cycle duration. Nevertheless the mean value of the period is surprisingly constant over a rather large time interval, at least several centuries and may be even millenniums.

The specific property of time dependency of each 11-year solar cycle is the existence of many other variations with higher frequencies making the time spectrum noticeably variable [Kononovich, 1999]. Noisy character of these variations is very similar to that observed in the case of variable stars. So usually one assumes them a noise and substrate by smoothing. However, recent results show, that the short time variations are physically significant.

Main components of the SA cycles

The solar 11-year cycles are very similar in general form and differ primarily in their amplitudes and duration. However, their fine structure is rather complicate. It includes a lot of short time variations. Nevertheless, these variations have several important features. The main one is the existence of two noticeable maxima at the beginning of each cycle. To the end of the 11-year cycle the width of the individual maxima diminishes. On the other hand, the 11-year solar maxima show a long-term variation. This suggests the existence of the secular variation, which was noticed at the beginning of the XIX century.

Schuster [1906] noticed the fine structure of the solar activity cycles. He revealed features with 2.7 years period. Later Gnevyshev [1966, 1977] using solar corona intensities showed a bimodal nature of the 11-year cycles 17 – 19 with the time intervals between the maxims 2 – 3 years. Nowadays these pioneer results are advanced by a large number of works, which revealed the remarkable fact that many geophysical processes also show variations within the same time interval [e.g. Kalinin, 1952; Shapiro and Ward, 1962; Sleptzov-Shevlevich, 1969; Apostolov, 1985; Labitzke, 1987; Ivanov-Kholodny et al., 2000; Baranov et al., 2001]. All variations treated in these works are well known as quasi-biennial variations (QBO).

Fourier analysis, performed by means of the Maximum Entropy Method (MME), reveals a lot of unstable frequencies corresponding to the range of periods from 3 to 0.7 years [Kononovich, 1999]. Noisy character of these variations is very similar to that observed in the case of variable stars. So, usually one assumes them to be a noise and ignores them by smoothing.

As a result one may suggest that at least three different processes may be more or less connected, compiling the observed SA variations. Also they include a lot of the noise component. The procedure of their extraction from a time series is very important. To decompose the original set of the monthly mean Wolf numbers W into several components it is possible to use the well-known method of main components [Kononovich et al., 2002]. In this paper only the QBO results are treated.

The thick lines in Figure 1 present the results, obtained by the above-cited method for six cycles (12 –17). It is easy to notice from Figure 1, that for all these cycles the QBO components are very similar. Their main feature is the existence of at least two prominent maxima with nearly equal amplitude and diminishing of their width.

The time interval between them is about 2 years just corresponding to the bimodal character of the solar cycle mentioned above. But, the width of the second maximum is lower. These two maxima form the basis of the QBO. A more attentive comparison shows a lot of similar but perturbed details. However, it is more difficult to recognise them because of strong noise distortions. Nevertheless, it is possible to conclude that in general the QBO component for all solar cycles corresponds to a certain fading wave train.

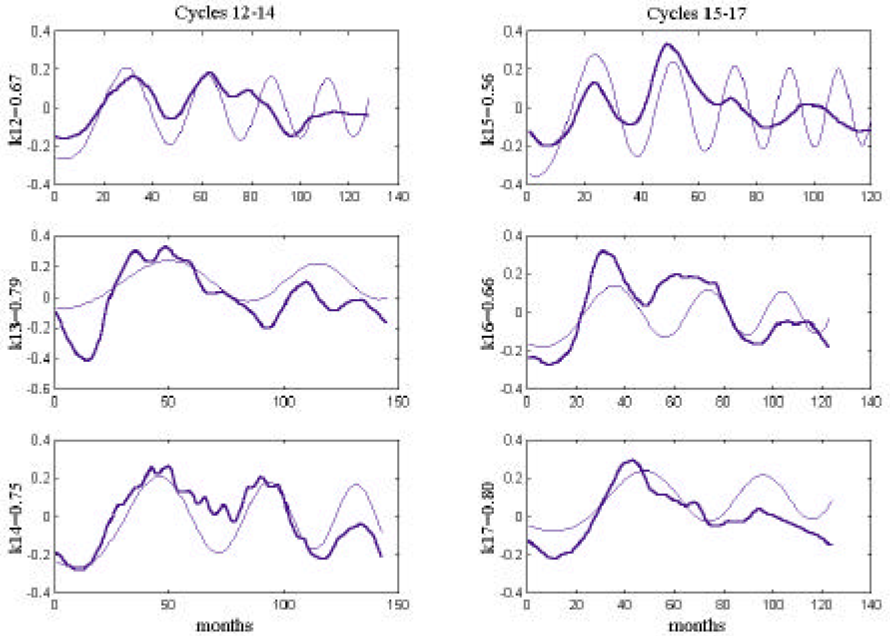

Figure 1. Presentation of QBO (thick lines) by Airy functions (thin lines) corresponding to the equation $y = -Ai(-k\,x+l\,)$. The x values are in months, y values are in arbitrary scale. The coherence coefficients are shown leftward of each panel.

QBO presentation by Airy functions

The remarkable properties of the QBO curves can be presented by the Airy functions well known in hydrodynamics and applied here for the interpretation of the solar QBO. These functions represent wave trains with diminishing amplitudes and periods of consequent picks [Abramowitz and Stegun, 1964]. Thin lines in Figure 1 present the graph of the analytical function $-Ai(-x)$, where the Airy function $Ai(x)$ is the solution of the nonlinear differential equation:

$$y'' - x\,y = 0,$$

given by the integral

$$Ai(x) = \frac{1}{\sqrt{\pi}} \int_0^\infty \cos\left(\frac{v^3}{3} + vx\right) dv.$$

The point of the broad curve minimum corresponds to the moment of the 11-year cycle minimum, i.e. the beginning of the current cycle. It is evident, that the left side of this slope suppresses the end of the previous cycle. On the other hand, at the right side all functions are truncated about 8-th – 12-th maxima. This corresponds to the end of the next cycle. As a result, each wave trend presented by a function $-Ai(-x)$ covers a pair of the 11-year cycles [Kononovich, 2001]. This agrees to the rule proposed by Gnevyshev and Ole [1948], who noticed that the beginning of the next solar cycle is connected with the end of the previous one.

All these relations suggest that it is much better to present the QBO by the superposition of the individual $-Ai(-x)$ functions. Only slightly adjusting the length and zero points of the individual Airy functions it is possible to obtain similarity in small details though not always with the same amplitudes.

Upper atmospheric data

The behavior of temperature in the region of mesopause and lower thermosphere was analyzed to obtain the QBO properties and their connection with quasi-biennial variations of solar activity. The emissions characteristics variations measurements of the hydroxyl, atomic sodium 589.3 nm and atomic oxygen 557.7 nm were made at stations Zvenigorod and Abastumani. Temperature and intensity of hydroxyl emission were determined using its radiative spectrum in the range of bands (5-2) and (8-3). The estimation of temperature for the 557.7 nm emission was made using the intensities of the 557.7 nm emission. The data about temperature value at 92 km level were determined by means of the analysis of the atmospheric sodium emission behavior.

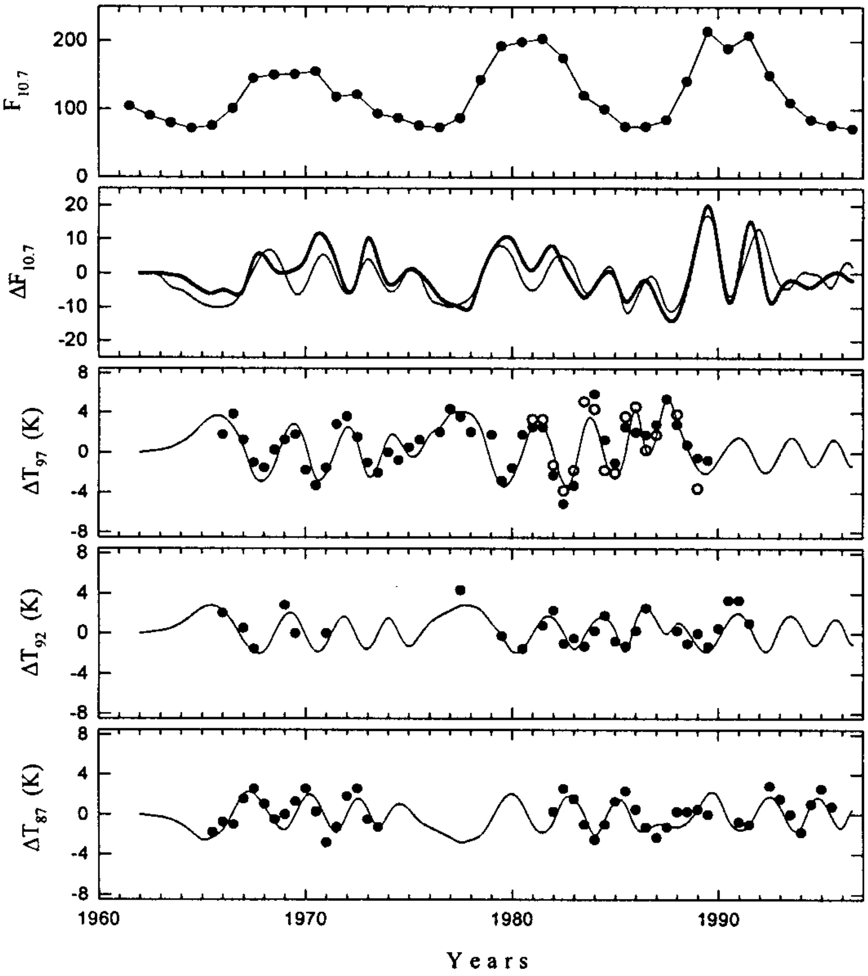

Figure 2. QBO of the temperature ΔT at heights 97, 92, and 87 km according to spectrophotometric measurements of the emissions of the atomic oxygen 557.7 nm, atomic sodium 589.3 nm, and hydroxyl, respectively (black circles). Open circles show the data of the interferometric temperature measurements in Yakutsk by Yugov et al. [1997]. The mean annual variations of the $F_{10.7}$ are shown at the top panel and their quasi-biennial variations $\Delta F_{10.7}$ [Ivanov-Kholodny et al., 2000] are indicated below by thick solid line. Thin lines are approximations by Airy functions.

To reveal the QBO the time series analysis technique presented in [Ivanov-Kholodny et al., 2000] was used. Here it was taken into account, that the signals are not strictly harmonic. The temperature variations ?T of the emissions of the atomic oxygen 557.7 nm (~97 km), sodium (~92 km) and hydroxyl (~87 km) are shown in Fig. 2 by black circles. For comparison the open circles in Fig. 2 present the ?T data obtained by interferometric measurements of temperature of emission 557.7 nm in Yakutsk [Yugov et al., 1997]. One may note the correlation between these ?T series and their time presentation. It is known that the temperature regime of the lower thermosphere is formed by the variations of intensity of solar UV radiation, which are closely connected with a solar activity. Therefore, to describe the obtained QBO in the atmospheric temperature variations it may be plausible to take into account the above-considered existence of the QBO in the solar activity parameters. Thus all discussed variations are equally satisfactorily presented by the Airy functions (thin lines in Fig. 2).

Discussion

The main result is that the similar wave trains of the quasi-biennial variations are the main property of the fine structure of the 11-year SA cycle. In each case these variations are a superposition of a triad of consecutive, nearly equal extinction wave trains appearing regularly with 10 – 11 years interval. The main wave train begins shortly before the end of the previous cycle. Its two front maxims are amplified by the interference with the end of the previous wave train. This leads to the well-known bimodal structure of the 11-year cycles. The deep and broad minimum of the following wave train suppresses the current cycle determining the exact moment of its minimum and of the following cycle beginning. The wave period is about 38 months at epoch of SA maximum linearly diminishing to 21 months toward the cycle end. The separate wave trains are well presented by the analytical Airy functions. Thus, the quasi-biennial variation of atmosphere temperature at the height of 87-97 km are very likely caused by the QBO of the solar activity due to the variations of the solar UV radiation absorbed at heights of the lower thermosphere. The origin of the outlined structure is by no means connected with the dynamical processes in the deep layers of the Sun and presumably those in the convection zone pattern.

Acknowledgment. The authors thank V.K. Roldugin for valuable comments. This work was supported by the Russian Federal Program "Integration", contract 507.

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