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SOME FRESH INDICATIONS OF THE SOLAR ORIGIN OF 4-6-YEAR OSCILLATION OF THE EARTH'S ROTATION PARAMETERS

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SUMMARY: The variations of universal times difference UT1-TAI and Earth's rotation instantaneous pôle coordinates (X,Y) are studied in the frequency range of 3 - 8 yr^{-1} as a function of the solar activity. It is found that power spectrum concentrations C_1 and C_2 are common to solar activity indicators and Earth's rotation parameters (ERP). The linear correlation between them is also not a fortuitous one. Accordingly, by the results of this study the hypothesis of Djurovic and Pâquet (1996; 1999) that the primary cause of 4-6 year oscillation lies in solar irradiance is confirmed.

Between several mechanisms responsible for the ERP variations as the most probable are considered the variations of solar irradiance spectral structure (especially large in its UV range) and variations of intensity of cosmic X-rays reaching the Earth's surface.

1. INTRODUCTION

The five year oscillation (FYO) whose period is variable with the power spectrum maximum at 4-6 years has been detected in universal times UT1-TAI difference (Djurovic and Pâquet 1990; 1993; 1996), in the length of day (LOD) (Dickey et al. 1994) and coordinates (X,Y) of the instantaneous Earth's rotation pole (Abarca et al. 1994).

According to Dickey et al. (1994) the FYO in LOD is caused by the quasi-biennial (QBO) and El Niño/South Oscillations (ENSO) winds. The coherence between X-coordinate and the corresponding atmospheric effective angular momentum function (χ_1), found in Abarca et al. (1994), is in accordance with the Dickey's et al. (1994) assumption that the FYO origin lies in the atmospheric circulation.

Besides the new results by which the FYO of X,Y and UT1-TAI is verified, in Djurovic and Pâquet (1996; 1999) is reported that this variation is present in the residuals of some solar activity indices computed with respect to the best fitting sinusoid of 11-year cycle. The detection of FYO and some other common oscillations of the solar activity, geomagnetic indices, atmospheric effective angular momentum functions and Earth's rotation parameters (ERP) (the 50-day, the 4-month, the quasi-biennial oscillations, etc), as reported in Djurovic et al. (1994), Djurovic and Pâquet (1988; 1989; 1993) allows us to assume that the primary cause of the mentioned geophysical oscillations lies in the solar activity. The probable perturbing mechanisms are: 1). the interaction between the variable UV radiation, atmospheric ozone and tropospheric circulation; 2). the changes of the sectorial structure of interplanetary magnetic field, related to the evolution in time of sunspots, and changes of the cyclonic activity; 3). the changes of the cosmic X-ray intensity at the Earth's ground, which is anticorrelated with the solar activity, and corresponding air particles ionization which could be responsible for the cloud formation and variable Earth's albedo.

The 11-year cycle can be approximated by the sum of two sinusoids (plus a constant term) whose periods are 11 and 5.5 years. This fact was already known (Bloomfield 1976). As reported in Djurovic and Pâquet (1999) this characteristic of the main cycle is particularly well pronounced in the periods of high activity, while in the periods of lower activity the part of power spectrum between 3-8 years is less concentrated and its maximum appears with the period of about 4 years. In the same study it is pointed out that the power spectrum maxima of the polar coordinates of International Latitude Service (ILS) are at around 4 and 5.5 years. The last result is confirmed in the case of IERS coordinates, analysed in this work. It is understood as an indication that the atmospheric circulation and ERP are perturbed by the variable solar activity.

The main task of the present work is to obtain new results which can be useful in solving the enigma of whether the atmospheric, geomagnetic and Earth's rotation variations are really related to the evolution in time of sunspots or to the assimetry in the growing and declining part of 11-year cycle of the solar activity, as assumed in Djurovic and Pâquet (1996; 1999). For this purpose the new Earth's rotation and solar activity data are analysed.

2. DATA AND COMPUTING METHODS

The data analysed in this study are:

a) Instantaneous pôle coordinates (X,Y) and UT1-TAI of the International Earth Rotation Service (IERS) for the period 1962.0-1997.5 (file: eopco2).

b) Wolf numbers (W) for the period 1962.0 - 1997.5, provided by Sunspot Index Data Center, Brussels (file: dailyssn).

c) Solar 10.7 cm flux (FLX), adjusted values, for the period 1962.0 -1997.5, provided by NOAA (Boulder, Colorado), file: flux.

d) Geomagnetc index Aa for the period 1962.0 - 1994.0, also provided by NOAA, file: aaindex.

In Djurovic and Pâquet (1996; 1999) the IERS series of UT1-TAI for the period 1962.0-1994.0 and the series of (X,Y) of the International Latitude Service (ILS) are analysed. In the present analysis the new X,Y and UT1-TAI data are included.

Since the Greenwich series of sunspot areas (SA) ends with 1981, the series of W is analysed as it spans the whole interval of IERS data. The coincidence of SA and W variations in the frequency range 3-8 yr^{-1} (e.g. Djurovic and Pâquet 1999) ensures that the essential results of this work are not corrupted by the use of index which is less appropriate for a study of correlations between the solar activity and geophysical events.

Besides W, as a general index of the solar activity, the 10.7 cm flux is particularly interesting because it is strongly correlated with the solar UV radiation. As mentioned above, the UV radiation is suspected to be one of probable disturbing factors of the global atmospheric circulation (McCormac and Seliga 1978).

The geomagnetic index Aa, whose variations are certainly caused by the corpuscular solar irradiance, is interesting for this study because geomagnetic instabilities are also suspected to be related with decade and some other interannual variations of the Earth's rotation (Munk and McDonald 1960; Laptuhov 1980; Stewart et al. 1995).

The methods used in this work are: the least-squares (LSQ), the cubic spline (CS) and Fourier series (FS) for data smoothing and filtering, Simpson's formula for numerical integration, Direct Fourier Transforms (DFT) for the spectral analysis and the linear correlation for testing of statistical dependence between variables.

3. FYO IN SOLAR ACTIVITY AND GEOPHYSICAL TIME SERIES

Let *the assimmetry of the main cycle* (AMC) be defined as the systematic discrepancy between the observed solar activity index and the 11-year sinusoid computed by the LSQ method.

To follow the evolution in time of AMC in the given solar activity index it is convenient to remove the sinusoid whose period is close to 11 years. For this purpose the 55-day averages of W, FLX and Aa are approximated by:

$$F = X_1 + X_2 sin\omega t + X_3 cos\omega t \qquad (1)$$

where $\omega = 2\pi/P$.

The period P is varied from 9.0 up to 13.0 years with the step of 0.2 year. For each value of P the unknowns X_k are computed by the LSQ method.

The best fitting sinusoid corresponds to the minimum of the standard deviation of residuals. These residuals are later used for the spectral and correlation analysis.

The above computations are performed independently for different cycles (from minimum to minimum).

The discontinuities at the junctions of the successive 11-year subseries are not important for the final results. This is controlled by smoothing and filtering of data by the Fourier series (FS) approximation without any data division into the subseries.

Relevant details related to the second method will be described later.

The 55-day averages of FLX, W and Aa are used instead of original data to avoid filtering of the Sun's rotation cycle and also to diminish random fluctuations. The data density still remains suitable for the study of FYO.

Since the residuals of Aa computed with respect to the best fitting main cycle sinusoid contain some short-period oscillations (semi-annual, annual, quasi-biennial, etc), they are smoothed by the FS method and the harmonics whose periods $P \leq 2.5$ years are subsequently removed.

For the series analysed in this work the differences between the results obtained by the FS smoothing which includes first N/3 harmonics, N being the number of data, and CS smoothing with the parameter $\lambda = N$ (Reinsch 1967) are not significant: in both of them the same systematic variations are preserved. This is shown in Fig. 1 in which the smoothed residuals of W and FLX, computed by two methods, are represented. The reason to use the FS method lies in its ability to easily filter the harmonics which are of particular interest.

The coefficients of FS are computed by the Simpson's formula of numerical integration. The accuracy of these solutions is equivalent to that attained by the LSQ method. Besides the simplicity, this method allows to avoid the known numerical problems related to the LSQ method when the determinant of the system of normal equations is close to zero.

The residuals of polar coordinates (Fig.2) used for the FYO analysis are obtained after removing linear trends and FS harmonics whose periods P < 2.9 (12th harmonics) and P > 8.8 years (4th harmonics): quasi-biennial, chandlerian, annual, semi-annual, etc.

The results of one-side filtering of X and Y by removing the FS harmonics whose P < 2.9 years, do not differ significantly from those presented in Fig.2. Therefore, the quasi-periodic variations of X and Y, evident in Fig.2, are not created by the filtering procedure.

To study the variation of UT1-TAI in the frequency range $3 - 8yr^{-1}$ it is convenient to remove the known constituents (the second order polynomial trend, the quasi-biennial and seasonal variations) and two unexplained quasi-sinusoidal variations whose periods are about 22 and 11 years. To justify this, in Fig.3 are presented the residuals R1, R2 and R3 defined by the equations:

$$R1 = UT1 - TAI - P_2 - H_1,$$

$$R2 = UT1 - TAI - P_2 - H_1 - S,$$

$$R3 = UT1 - TAI - P_2 - H_1 - H_2$$

where P_2 is a second order poynomial trend, H_1 is the sum of Fourier harmonics whose periods are less than 2.9 years (biennial, annual, semi-annual, etc), S is a 22-year sinusoid and H_2 is the sum of Fourier harmonics whose periods are larger than 8.8 years.

The residuals close to R3 can be obtained by increasing the polynomial term degree, instead of the sum $P_2 + S$. For example, the r.m.s of residuals computed with respect to the four and five degree polynomials and to the sum of second degree polynomial and 22-year sinusoid are:

polynomial of degree four: 0.155 s,

polynomial of degree five: 0.151 s,

polynomial of degree two + 22-year sinusoid: 0.117 s.

The above approximations of UT1 - TAI variation are not justified from the physical point of view, but their filtering allows detection of the variations which are of particular interest for this study.

Since the time variations of residuals of solar activity and geophysical series have a quasi-sinusoidal character (Figs. 1, 2, 3), some complementary information is obtained by computing their spectra (Fig.4).

The DFT spectra of the solar activity and geomagnetic residuals (also presented in Fig.4) are computed for the same observation period for which IERS data are given. This restriction facilitates detection of eventual common oscillations.

The maxima C_1, C_2 of the variable $Q = (A/s)^2$, where A is the amplitude and s standard deviation of residuals, are clearly standing out in Fig.4 and statisticaly significant in all spectra. If the analysed series represent a white noise, the upper limits of Q computed by the known Schuster's formula (Schuster 1898; Djurovic and Pâquet 1993) for the probability Pr=0.999 should be: 0.06 for the Earth's rotation parameters and 0.12 for WLF, FLX and Aa indices.

The maximum values of the linear correlation coefficient (ρ) and the corresponding time delay of the Earth's rotation response (τ) with respect to FLX and Aa variations are given in Table 1. The correlation coefficient is computed for the subintervals 1962-1978 and 1979-1997 because it was noticed that the sign of ρ changes at the epoch $t_0 \approx 1979.0$.

Table 1. Correlation coefficients:ρ_r for raw residuals, ρ_s for smoothed residuals.τ-the phase difference in years

Observation period: 1962.0 - 1979.0

	ρ_r	τ	u	ρ_s
$X - FLX$	+0.42	1.46	6.21	+0.66
$Y - FLX$	−0.45	1.38	6.64	−0.59
$UT - FLX$	−0.78	1.56	14.36	−0.82
$X - Aa$	+0.41	1.38	5.87	+0.76
$Y - Aa$	−0.16	1.38	2.26	−0.32
$UT - Aa$	−0.45	1.56	6.53	−0.62

Observation period:1979.0-1997.5

	ρ_r	τ	u	ρ_s
$X - FLX$	−0.58	1.63	9.57	−0.80
$Y - FLX$	−0.53	6.31	7.40	−0.63
$UT - FLX$	+0.66	7.64	9.37	+0.70
$X - Aa$	+0.18	2.20	2.37	+0.34
$Y - Aa$	+0.36	1.38	4.96	+0.58
$UT - Aa$	−0.38	3.28	4.98	−0.62

Theoretically, if two Gaussian variables are mutually independent the probability that the parameter:

$$u = \left| \frac{\sqrt{N-3}}{2} ln \frac{1+\rho}{1-\rho} \right| \qquad (3)$$

will be less than 2.575 is Pr=0.99 (Bendat and Piersol 1971). As shown in Table 1, the above limit is exceeded, except for the pair (Y, Aa) in the first and the pair (X, Aa) in the second subinterval. Therefore, the EOP parameters are statistically dependent on the solar activity, while for the geomagnetic and EOP series such relationship is not clear.

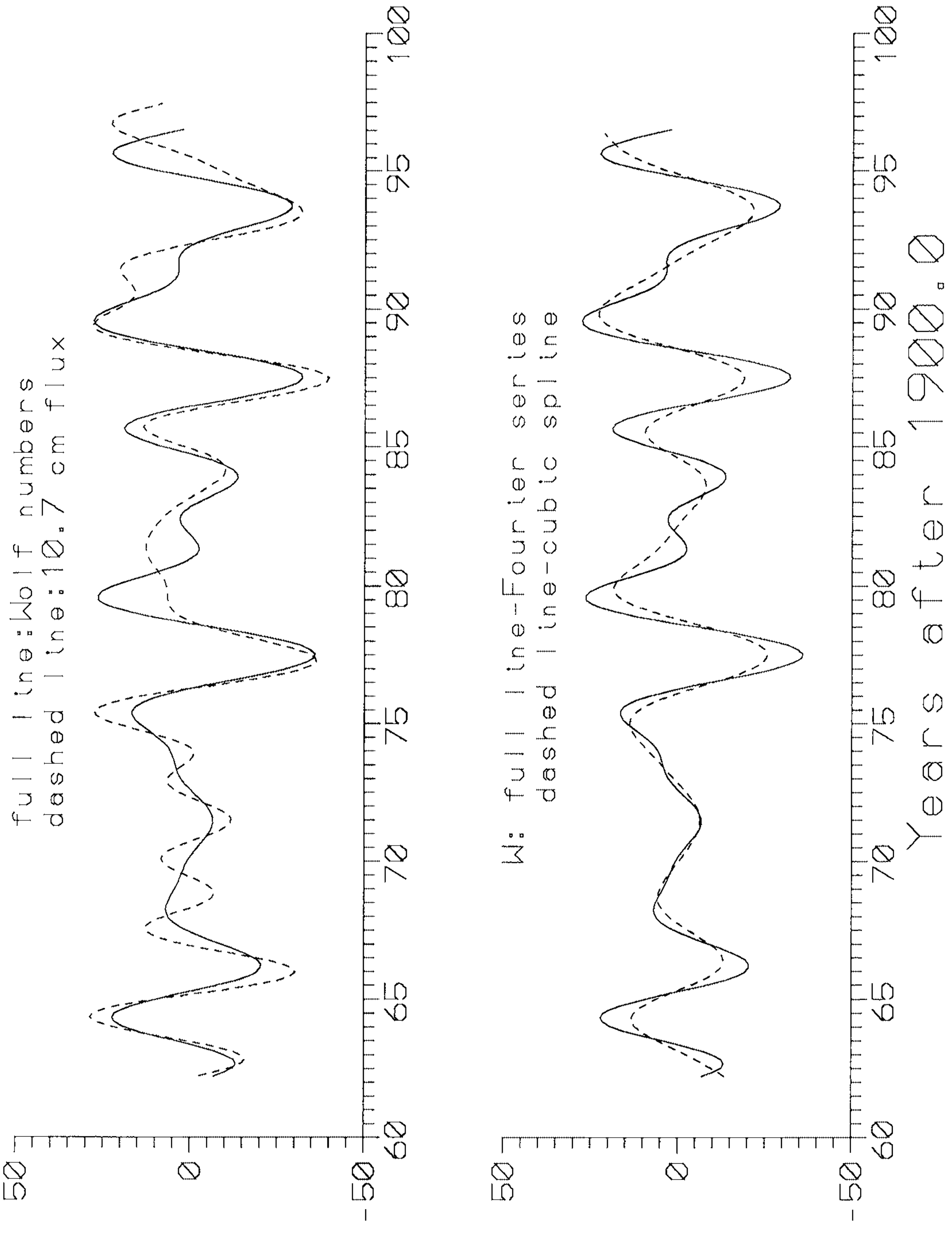

Fig. 1. *Smoothing of Wolf numbers and solar 10.7 cm flux by the cubic splines and Fourier series.*

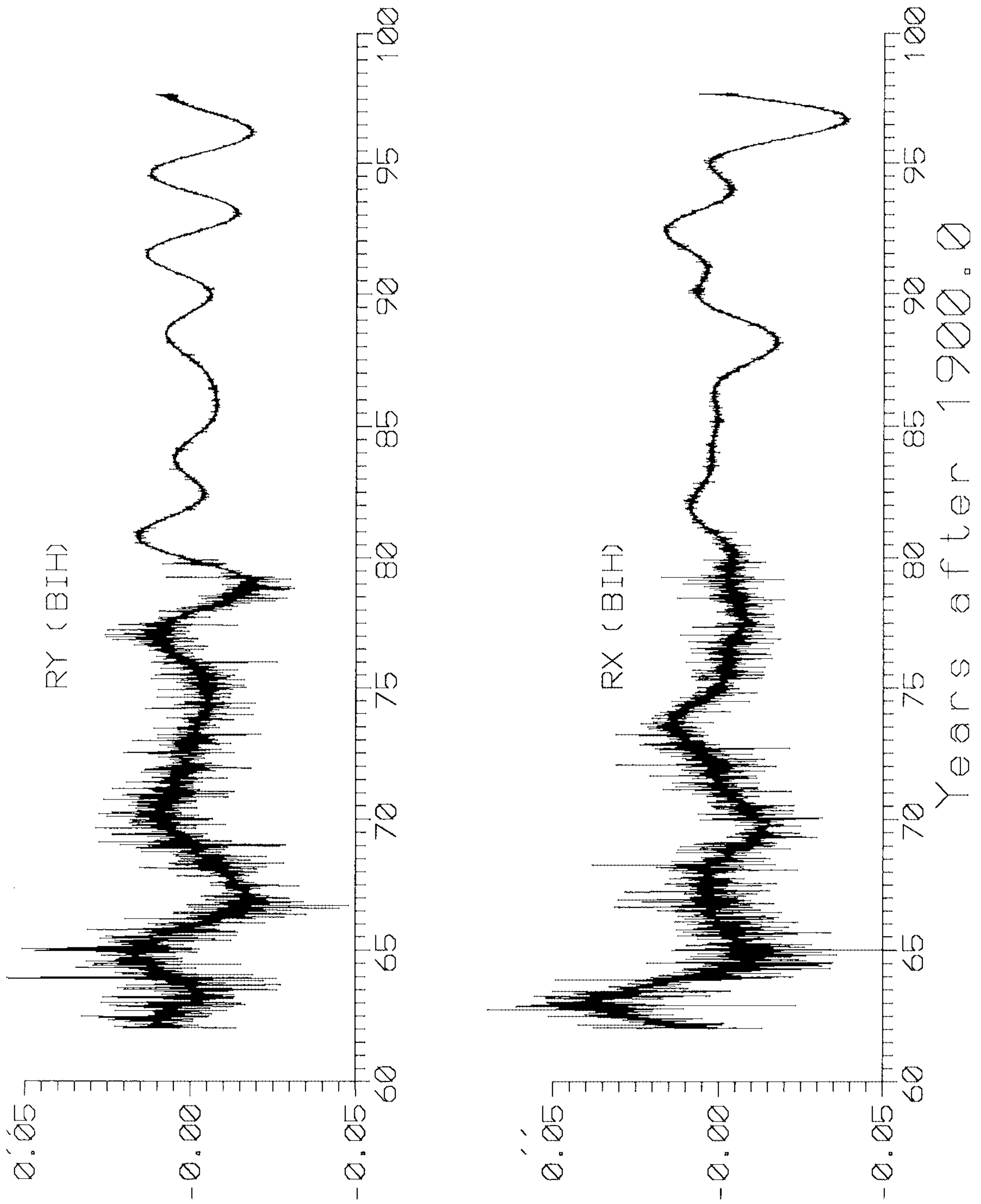

Fig. 2. *Residuals of polar coordinates after the filtering of linear trends and oscillations whose periods are less than 2.9 years or larger than 8.8 years.*

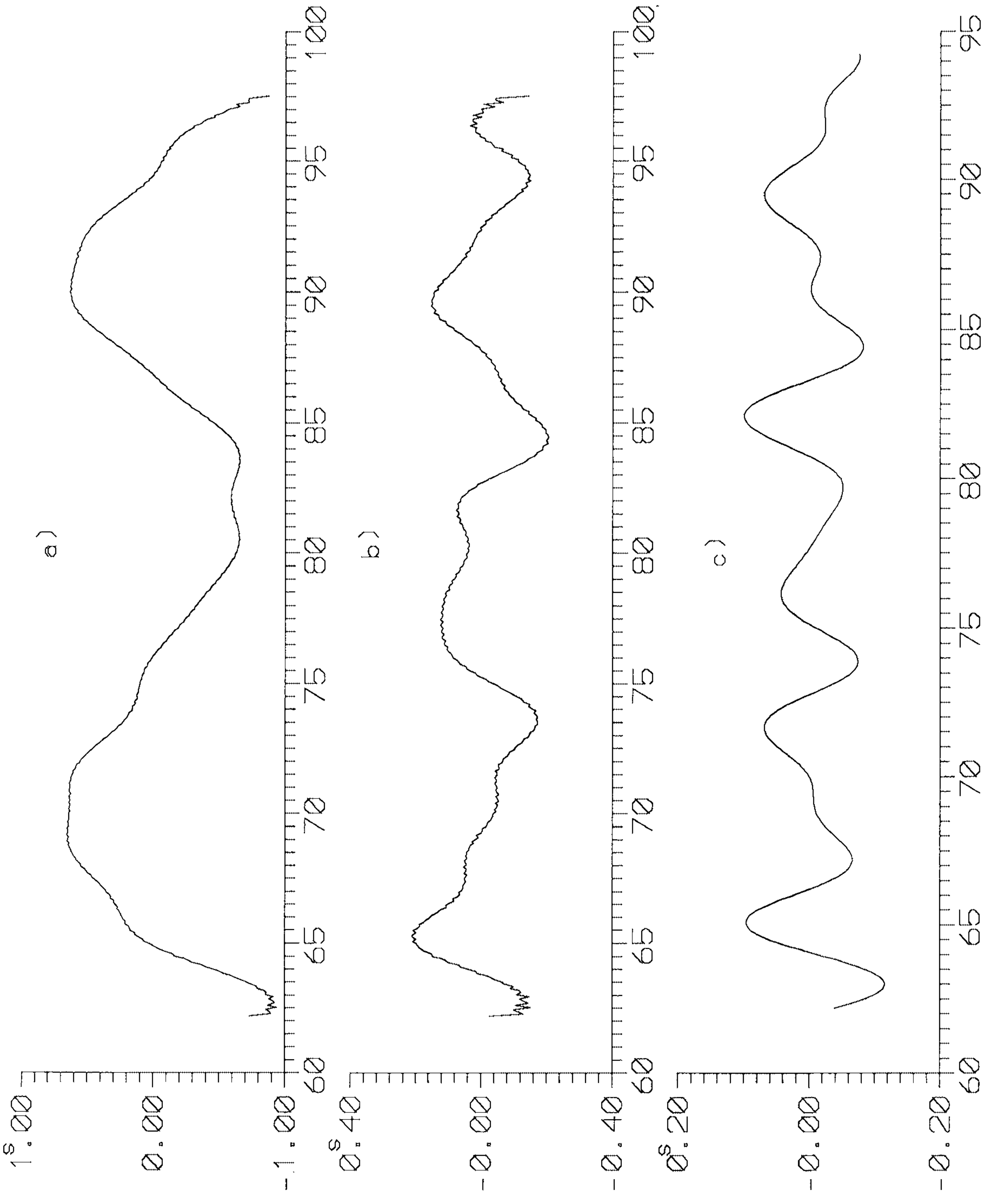

Fig. 3. *Residuals of UT1-TAI after the filtering of a) second order polynomial trend and oscillations whose period are less than 2.9 years; b) second order polynomial trend, 22-year oscillation and oscillations whose periods are less than 2.9 years; c) second order polynomial trend and oscillations whose periods are less than 2.9 years or larger than 8.8 years.*

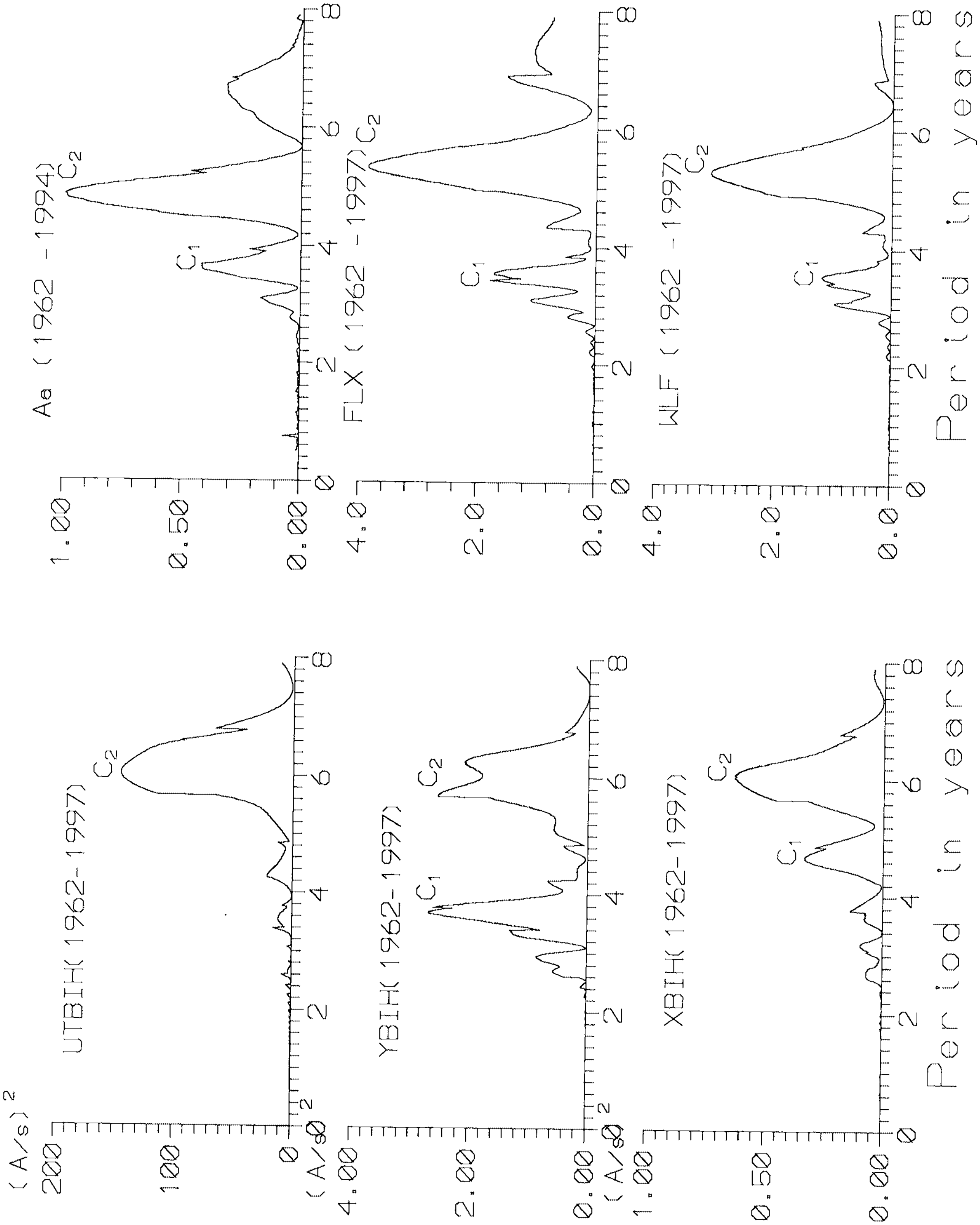

Fig. 4. *Spectra of EOP, geomagnetic and solar activity indices.*

4. DISCUSSION OF THE RESULTS

According to the above said about the 11-year cycle asymmetry, the presence of power spectrum concentrations (C_1, C_2) in the spectra of the solar activity and geomagnetic series is *a priori* expected. The presence of both of them in EOP spectra (Fig.4) lends suggestion that the solar activity effects in the Earth's rotation are significant. Accordingly, our results obtained recently (Djurovic and Pâquet 1996; 1999) are verified. As remarked in Djurovic and Pâquet (1999), during the high activity cycles the FYO period is about 5.5 years. In lower cycles, like the cycle No 20 (1965-1976) (included in this study) the power spectrum maximum is around 4 years.

Besides the well pronounced power spectrum concentrations (C_1, C_2), the non-zero correlation coefficients also offer an indication that the solar activity is a source of the Earth's rotation disturbances.

The hypothesis of the solar activity contribution in EOP variations is additionally supported by the presence of other oscillations observed in both the solar activity and geophysical time series. The most convincing oscillation is that of about 50 days period, detected in radiometric NIMBUS-7 and SMM/ACRIM records and projected areas of active sunspots (Wilson 1982, Pap 1985, Pap et al. 1990). On the other hand, in the atmospheric circulation there is a known Madden-Julian oscillation (MJO) (Madden and Julian 1971), whose period is also about 50 days. Through the exchange of angular momentum between the atmosphere and the "solid" Earth, the MJO causes the corresponding LOD and universal time UT1 oscillations (Feissel and Gambis 1980; Langley et al. 1981; Djurovic 1983; Djurovic and Pâquet, 1988; Djurovic et al. 1994).

In addition to the 50-day variation, in some solar activity indices the quasi-biennial oscillation (QBO) is assumed (Djurovic and Pâquet 1993 and references therein). This oscillation could be related to the atmospheric QBO and quasi-biennial instability of the Earth's rotation (Iijima and Okazaki 1966; 1972).

The fascinating progress in the atmospheric and geomagnetic investigations during the recent decades provides independent indications in favour of the above mentioned hypothesis.

The systematic variations of the total solar irradiance throughout the 11-year cycle (Willson and Hudson 1988), detected in radiometric records from NIMBUS-7 and SMM spacecrafts, are of the order of several tenths of percent. In view of the small amplitude they are probably not directly responsible for the striking reactions of the Earth's atmosphere which are suspected to be the cause of FYO in polar coordinates and UT1-TAI. However, it is more realistic to assume the changes of irradiance structure, (particularly the large UV fluctuations) during the 11-year cycle as having an important contribution in the tropospheric changes.

In some meteorological studies it is assumed that the atmospheric ozone, which is certainly dependent on the UV radiation, is important for the state of troposphere (McCormac and Seliga 1978).

The second probable explanation of the common solar activity and EOP variations is related to the cosmic X-ray radiation reaching up the Earth's surface. On the other hand, it is well known that the solar activity produces a kind of Earth's shield against cosmic X-rays. In the language of statistics, solar activity and the cosmic X-ray intensity at the Earth's surface are anticorrelated.

Cosmic X-rays ionize the un-ionized tropospheric air, change its electrical conductivity and potential the between ionosphere and the Earth's surface. Since the condensation and freezing of water vapour into ions and electrically charged microscopic particles are influenced by the atmospheric electric field (Parker 1994, summary comments), it is probable that the changes of the tropospheric albedo and the warming of the Earth are related with the solar activity.

Direct effects of the solar activity, observed in the ionosphere and upper stratosphere, where the air density and temperature vary in the rhytme of the solar activity, are not clearly detected in troposphere. The studies of these effects are not successeful because the antropogenic pollution and volcanic activity cause changes of tropospheric structure and probably mask the "regular" changes due to the UV and X-ray irradiance.

The presence of solar activity effects in the troposphere becomes more acceptable if one bears in mind that small external excitations may produce striking atmospheric responses (Broecker 1989; White 1993).

The geomagnetic field disturbances, due to the corpuscular solar irradiance, could also be a way of solar activity influence on the Earth's rotation dynamics (see, for example, Munk and MacDonald 1960; Laptuhov 1980; Stewart et al. 1995 and references therein). According to Stewart et al. (1995), the most probable cause of decade LOD variations is the variable electromagnetic torque (EMT) acting on an electrically conducting mantle. They have found a clear correlation between the EMT acting on the Earth's mantle and the torque computed from astronomical observations of the Earth's rotation. The best correlation is found for EMT phase delay (with respect to the astronomical torque) of 6 years.

From the results presented in Table 1 one can assume that the "atmospheric" hypothesis is more probable than the "geomagnetic" one: the correlation coefficient between FLX and EOP series are above the corresponding values relative to Aa. In this sense it should be interesting to analyse the relation between the amplitudes and phases of ENSO and polar coordinates variations. In the spectrum of NINO3 sea surface temperature, which is a measure of the ENSO amplitude, computed by Torrence and Compo (1998), the most prominent peaks are at 3, 4 and 6 years.

As an argument often opposed to the hypothesis of significant solar activity contribution to the tropospheric circulation and the Earth's rotation is the absence of a strong 11-year cycle in their variations. However, this argument does not hold if one has in mind that the traditional indicators of the solar activity are not always good indicators of physical processes which have an influence on the state of troposphere and the magnetic field of the Earth. For example, the 50-day variation, well pronounced in the total irradiance and areas of active sunspot groups, is practically missing in areas of old decaying sunspot groups (Pap 1985; Pap et al. 1990). So, if the MJO is related with the 50-day oscillation of the solar irradiance, total sunspot areas are not an appropriate indicator for the study of the relation between them.

The second reason why the hypothesis of relation between the solar activity and Earth's rotation remains hardly acceptable lies in the lack of the convincing theoretical explanation of probable mechanisms acting between solar processes and tropostorr pheric circulation or the electromagnetic conductivity at the core-mantle boundary (CMB).

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НОВЕ ИНДИКАЦИЈЕ СУНЧЕВОГ ПОРЕКЛА 4–6 ГОДИШЊИХ ОСЦИЛАЦИЈА ПАРАМЕТАРА ЗЕМЉИНЕ РОТАЦИЈЕ

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Оригинални научни рад

Промене разлике светских времена UT1-TAI и координата тренутног пола Земљине ротације у опсегу фреквенција 3-8 год$^{-1}$ су анализиране у функцији Сунчеве активности. Показано је да постоје две заједничке спектралне концентрације (C_1, C_2) и да постоји неслучајна линеарна корелација међу њима. Тако је и овим радом потврђена хипотеза Ђуровића и Pâкеа (1996; 1999) да се примарни узрок 4-6 годишње осцилације налази у Сунчевом зрачењу.

Између неколико механизама одговорних за поремећаје параметара Земљине ротације највероватнијим се сматрају промена спектралне структуре зрачења (која је нарочито велика у UV домену) и промена интензитета космичког X зрачења на површини Земље.