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Short- and long- term periodicities of cosmic ray intensity time series

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Abstract: Galactic cosmic rays are energetic charged particles coming from outside the solar system, originating mostly from Supernova remnants. The aim of studying cosmic rays is the monitoring of the space weather conditions, so as to protect spacecraft and ground electronic systems and more importantly humans in space and in high latitude/altitude fights. Cosmic rays are detected by the ground based neutron monitor network in all over the world. In this work we examine short, mid and long term periodicities of cosmic ray intensity, sunspot numbers and geomagnetic Ap index for the time period 1976-2017 using Fast Fourier Transform (FFT) and Wavelet Analysis. The periodicities that are present in these two approaches regarding cosmic ray intensity are the well-known 11-year, which is caused by the anti-correlation with the solar activity and the 27-day and its harmonics due to the rotation of the Sun. The 5-year and the 1.7-year periodicity are also found with a significant level 95%. The last one belongs to quasi-biennial oscillations which are considered as one of the basic variations of solar activity indices on the scale of shorter than 11 years and probably they are intrinsic properties of the Sun related to the solar dynamo mechanism. The 5-year periodicity may be related to the 11-year as its first harmonic and belongs to quasi-periodic oscillations. Regarding sunspot numbers, except of the mentioned periodicities found in the cosmic ray intensity, the 2.3-year and the 5-month, known as Rieger period, were determined. The same results were applicable to the Ap index time series where the 6-month and the 1.3-year periodicity were found. Short scale variations such as the 5-6 months, are caused by transient effects in interplanetary space.

Data and Method of Analysis

The present analysis concerns the time period **1976** until **2017** covering **4** solar cycles and the following data have been used:

- 14884 solar sunspot number (SSN) measurements from WDC-SILSO, Royal Observatory of Belgium, Brussels *(http://www.sidc.be/silso/datafiles*).
- 15009 cosmic ray data from Neutron Monitor Database(NMDB) *(http://www.nmdb.eu/nest/).*
- 14610 data of Ap index from National Oceanic and Atmospheric Administrator (NOAA) *(ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/KP_AP).*

In order to study periodicities in these time series the following techniques have been used:

Fast Fourier Transform (FFT)

For time series $x_0, \ldots, x_{N-1}$ the Discrete Fourier Transform (DFT) algorithm has been implemented.

$$x_k = \sum_{n=0}^{N-1} x_n e^{-\frac{i2\pi kn}{N}}, \quad k = 0, \ldots, N-1$$

Solar Sunspot Number (SSN), Cosmic Ray intensity (CR) and Interplanetary Ap index have been examined.

Morlet Wavelet Analysis

Morlet Wavelet Analysis (*Torrence and Combo,1998)* for analyzing localized variations of power within a time series has been applied.

$$W_n(s) = \sum_{k=0}^{N-1} x_k \psi(s\omega_k) e^{i\omega_k n\delta t}, \omega_k = \begin{cases} \frac{2\pi k}{N\delta t}, k \le N/2 \\ -\frac{2\pi k}{N\delta t}, k > N/2 \end{cases}$$

ω_k : angular frequency, x_k : DFT of x_n

ψ: complex conjugate of Morlet function in the continuous limit , s: wavelet scale

Results

Solar Sunspot Number

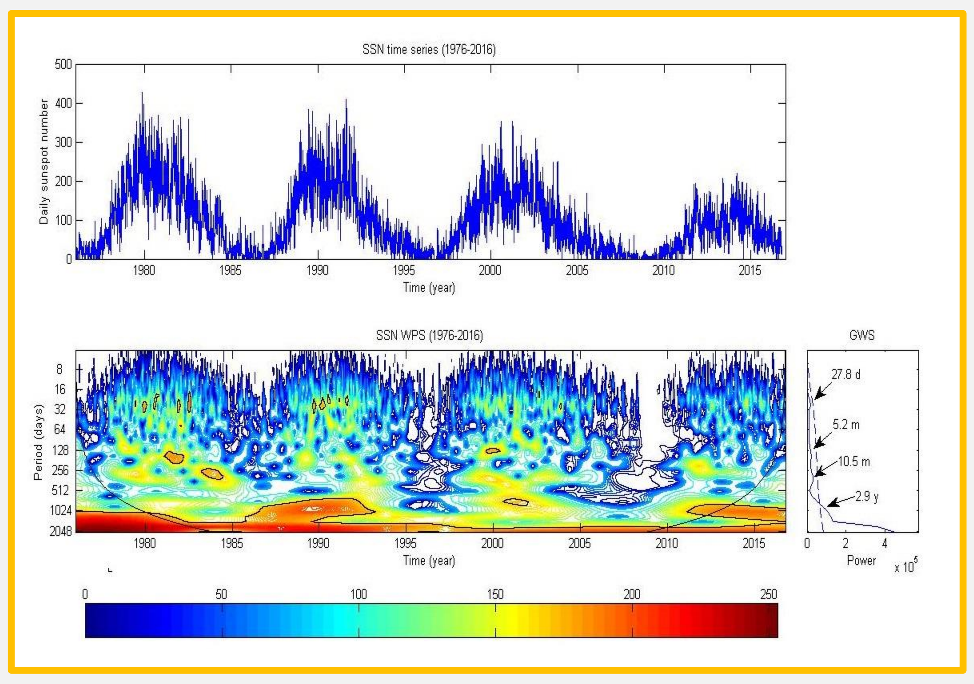

Fig. 1 Variation of daily time series of sunspot number during 1976-2016 (upper panel), Wavelet Power Spectrum(WPS)(middle panel), Global Wavelet Spectrum(GWS) (right panel). The cone of influence is shown in WPS. The dashed line in GWS represents the 95% confidence level. The color bar of the figure is also shown.

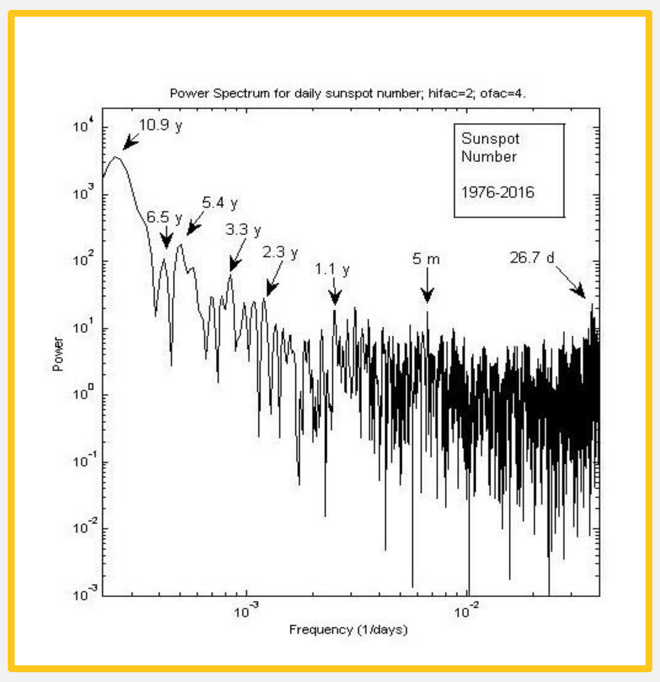

Fig. 2 Fast Fourier Power Spectrum of sunspot number during time period 1976-2016

Cosmic Ray Intensity

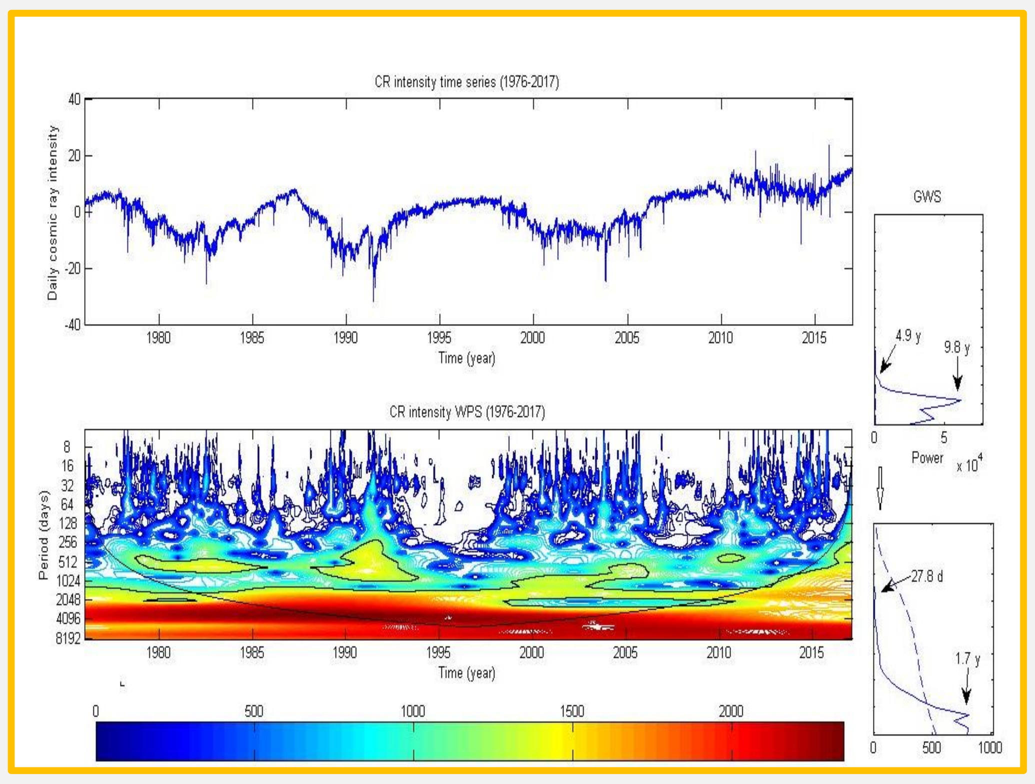

Fig.3 Variation of daily time series of CR intensity during 1976-2017 (upper panel), WPS (middle panel), GWS (right panel).

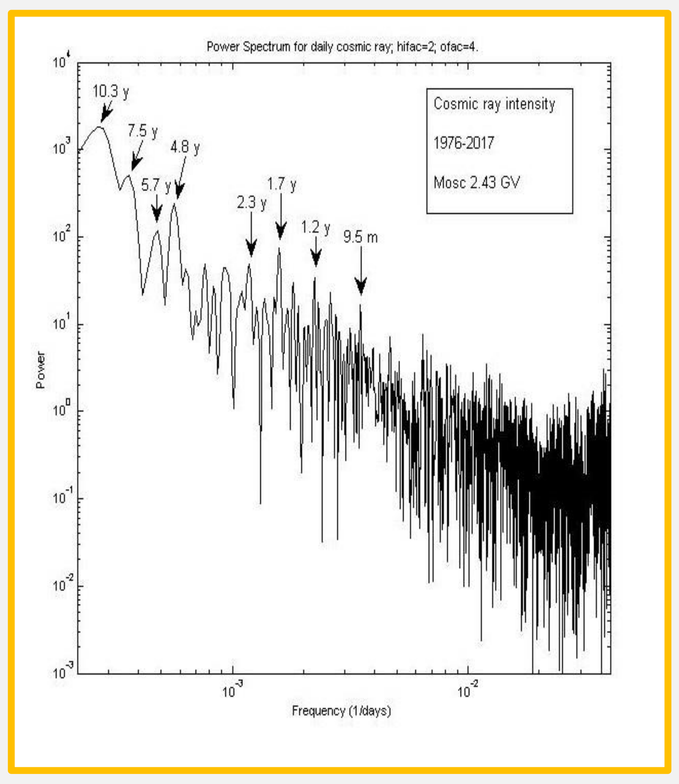

Fig.4 Fast Fourier Power Spectrum of CR intensity during time period 1976-2017

Ap index

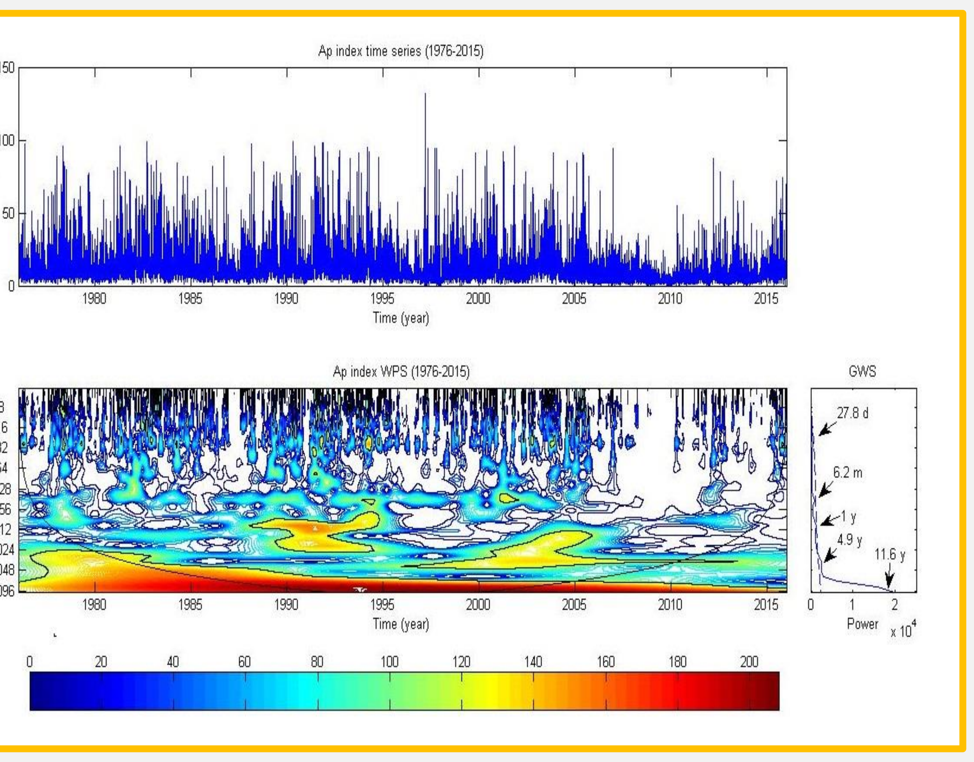

Fig. 5 Variation of daily time series of Ap index during 1976-2015 (upper panel), WPS (middle panel), GWS (right panel).

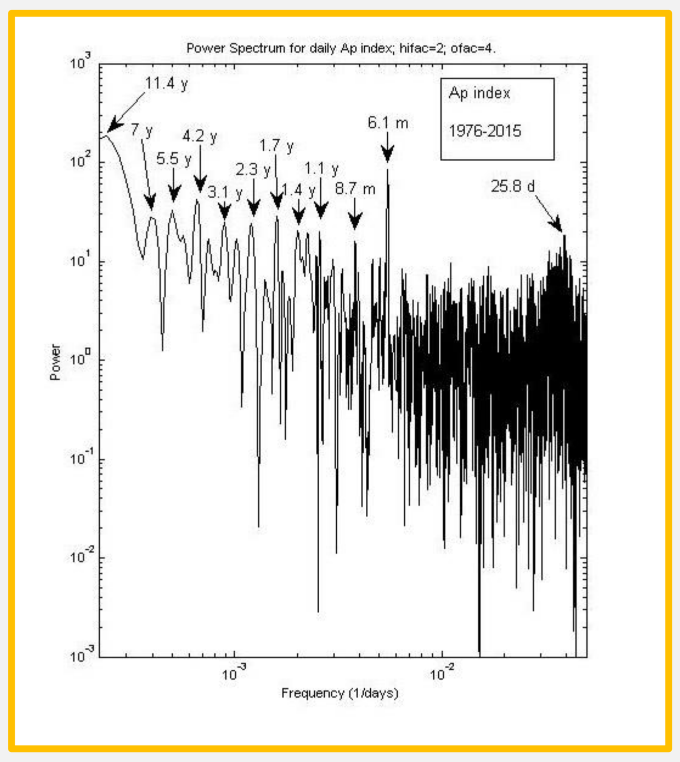

Fig. 6 Fast Fourier Power Spectrum of Ap index during the period 1976-2015

Results from WPS and FFT for all above parameters are shown in Table 1

Periodicity Time	SSN	CR	Ap index
Fast Fourier Transform (FFT) (Lombscargle)	*26.7 d* *5 m* *1.1 yr* *2.3 yr* *3.3 yr* *5.4 yr* *6.5 yr* *10.9 yr*	9.5 m 1.2 yr 1.7 yr 2.3 yr 4.8 yr 5.7 yr 7.5 yr 10.3 yr	9 d 13.9 d 25.8 d 6.1 m 8.7 m 1 yr 1.4 yr 1.7 yr 2.3 yr 3.1 yr 4.2 yr 5.5 yr 7 yr 11.4 yr
Wavelet Analysis	27.8 d 5.2 m 10.5 m 2.9 yr 4.9 yr 9.8 yr	27.8 d 1.7 yr 4.9 yr 9.8 yr	9.8 d 13.9 d 27.8 d 6.2 m 1 yr 4.9 yr 11.6 yr

Table 1: Significant peaks in SSN, CR and Ap index

Conclusions

- *The long term periodicity of 11-years is appeared in all examined parameters: SSN, CRI and Ap in both techniques, as it was expected.*
- *The short term periodicity of 27-days due to solar rotation is also revealed by both techniques in all parameters.*
- *The fundamental periods, like 5-month known as Rieger period and semi-annual are appeared only in solar parameters SSN and Ap index. This is resulted by the solar magnetic field which causes transient effects in the interplanetary space.*
- *All short and mid term periodicities of Ap index as shown on GWS from Wavelet analysis are smoother and clear during the examined period.*
- *The observed mid term ~1.3-year and 1.7-year founded in all above parameters are integral multiples of the Rieger period.*
- *The solar-rotation harmonics of Ap which was found can provide powerful information about space weather studies.*

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