Interpretation of Quasi Periodic Variations in Solar Cosmic Ray Data

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***Abstract*. Quasi periodic oscillations have been found in both solar and galactic cosmic ray data. In order to give an explanation for such variations we investigated the variability of the large-scale solar magnetic field. We applied the wavelet technique for spectral analysis of the photospheric magnetic field obtained from the National Solar Observatory at Kitt Peak, for the period 1977 ÷ 2004. The analysis was performed in 36 latitude bands. Several quasi-periodic oscillations in the range of about 2-4 yr were detected. We also tried to discriminate the fundamental modes of field variability from spurious components, by applying different filters to the data. Moreover, we located in solar latitude and height the space domain of the oscillations. The relationship between the variability of solar magnetic field and the solar cosmic ray flux is discussed.**

***Keywords*: Solar magnetic field, solar cosmic rays, wavelet analysis**

I. INTRODUCTION

The so-called quasi-biennial oscillations (QBOs) incorporate quasi-periodic variations in the range of 1.5-3 yr appearing in many manifestations of solar magnetism. A ∼ 2 yr periodicity was identified in non-symmetrical spherical harmonics of the photospheric field [1], [2]. Moreover, Ref. [3] showed that also axisymmetric modes have pronounced biennial oscillations, during the maxima of solar cycles 20-22 (and possibly also during the current cycle 23), with a period of 2.3 ± 0.2 yr for odd modes with coefficients l = 5, 7, 9 and for the even ones with l = 6, 8, 10. The amplitude of this biennial oscillation resulted to be modulated by the 22 yr cycle. This possibly indicates that the biennial oscillation might be a feature of the dynamo that has not yet been accounted for in models. Ref. [4], [5], analyzing data of the solar magnetic field polarity derived from H_α observations in 1915-1999, found that quasi biennial oscillations correspond to processes in the solar atmosphere with the largest spatial scales, which manifest only in low (global) harmonics (l=1, 2, 3). Ref. [6] used the method of independent component analysis (ICA) to extract underlying basic modes from the solar surface magnetic field fluctuations and to analyze their characteristic periods. They found dominant structures with quasi periodicities between 1.6 yr and 1.8 yr, during the declining phase of solar cycle 21. These structures appeared around 10°-50° latitudes and are dominant in the Southern hemisphere.

QBOs were found in many other solar and heliospheric phenomena (e.g. [5], [7], [8], [9], [10]), such as sunspot number, coronal green line emission, solar wind fluctuations, interplanetary magnetic field (IMF) intensity and galactic cosmic ray flux. In particular, Ref. [11] identified QBOs in the number of Hα flares, the solar magnetic field energy index and the sunspot areas. They also showed that the absolute amplitude of QBOs depends on the 11-year cycle phase, reaching its maximum in the maximum activity phase. The quasi-biennial variation has been detected also in the occurrence rate of solar energetic particle events [12] and the energetic proton fluxes recorded in the interplanetary space [13]. From the observation of the solar wind speed 1.7 yr fluctuations, it was deduced that such signal originates at low and middle latitudes [14]. A similar periodicity was found in λ 10 cm solar flux data [15] during 1970-1975, while it is less prominent at other times and seems to merge into a ∼ 3 yr periodicity. Ref [16] found that periodicities observed in the range 1.5-4 yr, could be the manifestation of the temporal modulation of an unique quasi-biennial periodicity.

On the other hand, Ref. [17] had proposed the phenomenological model of the double magnetic cycle on the Sun, by describing the radial component of the poloidal field as the superposition of two dynamo waves: a low-frequency component (22 yr cycle) and a high-frequency (quasi-biennial) component. The low-frequency component can be generated at the base of the convective zone due to large-scale radial shear of angular velocity. The high frequency component may be generated in subsurface regions due to latitudinal shear or due to a radial shear. It was assumed that the erupted low-frequency magnetic field can influence the physical conditions in the region of generation of the high-frequency component. If such influence is relatively weak, pronounced quasi-biennial components (in both the magnetic field and helicity) exist in the solution of the dynamo equations, along with the main 11 yr period. Also on the basis of nonlinear theories, stable frequencies with periods shorter than that of the 11 yr cycle may occur [18], suggesting that the 2 yr periodicity may be real. Ref. [19] supported the double-cycle solar dynamo model by investigating sunspot activity. Nevertheless, Ref. [20] have shown that quasi-periodicities in the range ∼ 1-3 yr may be due to stochastic processes associated with the emergence of active regions.

In the present paper we study the existence of QBOs in solar magnetic field data and their behaviour with heliographic latitude and time. Moreover, we investigate the connection between variations in the solar field and modulation of the solar energetic particle (SEP) fluxes, i.e. low-energy (about 10^7 - 10^{10} eV) cosmic rays seen as a distinct population in the interplanetary medium.

II. Data and Method

As a first step of our work the following data were retrieved:

- Daily Royal Greenwich Observatory - USAF/NOAA sunspot areas (in unit of millionths of a hemisphere) for the Northern and the Southern hemispheres, separately [1], covering the period 1977-2004.

- Data collected by the CPME instrument, aboard Interplanetary Monitoring Platform 8 (IMP 8) orbiting at ~ 35 Earth radii in the period from 1974 to 2001. We used only data from channels P2 ($0.50-0.96$ MeV) and P11 ($190-440$ MeV), that were not affected by the experiment malfunction occurred in 1989, as discussed by [21]. Perhaps, these channels give the basic information on interplanetary protons, being placed, respectively, in the low and high portions of the measured energy range. Data have been taken in the form of hourly averages from the Web site of the Johns Hopkins University [2]. Most of the spurious signals, such as those occurring during the spacecraft crossings of the magnetosphere, were already removed by the investigators. Nevertheless, several spikes were still present, whose instrumental origin was revealed by their short duration ($<$ 1 h). After removing these spikes, we averaged data over each Bartels Rotation (BR), obtaining, in both channels, a continuous coverage from BR 1921 to BR 2291 (i.e., from 14 January 1974 to 17 June 2001).

- Magnetic synoptic maps, derived, one per Carrington Rotation (CRot), from the daily full disk photospheric magnetograms taken at the National Solar Observatory of Kitt Peak (NSO/KP) [3]. The series starts with CRot 1601. However, the synoptic maps from CRot 1601 to CRot 1648 present many data gaps and they seem not properly calibrated. Hence, we considered only data from CRot 1649 to CRot 2007 [December 4, 1976 - September 26, 2003]. Each map represents the line of sight component (B) of the solar magnetic field in heliographic coordinates and consists of 360×180 pixels, with a spatial resolution of $1^\circ \times 0.011$ in longitude$\times$ sine latitude. From the magnetic maps we constructed a lower resolution data set, by averaging the field over a $5^\circ \times$ 0.055 boxes. This procedure allows to reduce the majority of data gaps. They were not not eliminated in only four CRots and thus were filled by using the average of the photospheric field at the same location from the preceding and following rotation. Because the time changes of the large scale fields occur on long time scales we believe that this procedure lead to a reasonable approximation of the real field.

[1] http://solarscience.msfc.nasa.gov/greenwch.shtml
[2] http:// sd-www.jhuapl.edu/IMP/imp_cpme_data.html
[3] ftp://nsokp.nso.edu/kpvt/synoptic/mag/

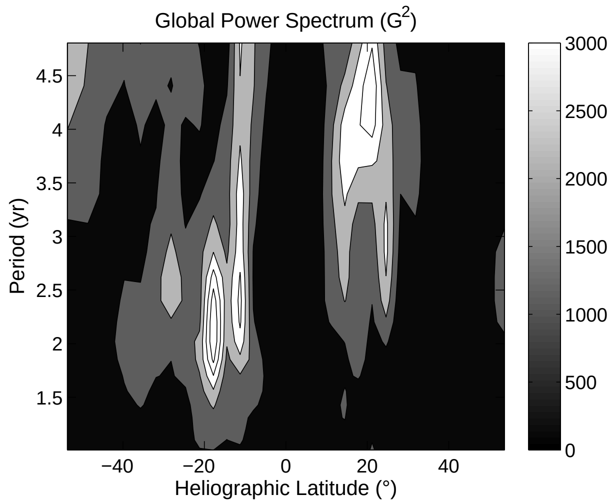

Fig. 1: Global wavelet power spectrum of the NSO/KP magnetic field as a function of the central heliographic latitude.

The resulting data set is composed of 36 time series (corresponding to different latitudes zones), each of them having 25848 points equally spaced by a time step of 0.3788 d (as we averaged B over the 5° longitude bins). Then we smoothed data by calculating running mean over 143 pixels in longitude (i.e. over 54.16 d), thus applying a high pass filter to each time series of our grid to investigate variations longer than at least two CRots. Then, we performed the wavelet analysis [22] to the time series corresponding to the different available latitudes.

The local Wavelet Power Spectrum (WPS) was calculated, choosing appropriate wavelet parameters (Morlet mother wavelet with $\omega_0 = 6$; $J = 96$ and $dj = 0.125$ resulting in 97 periods from 0.78 d to 8.81 yr), to decompose each one-dimensional time series into a two-dimensional time-frequency space. We computed also the Global Wavelet Power Spectrum (GWPS), analogous to the Fast Fourier Transform, to readily identify the frequency of (quasi-) periodic signals over the whole available period. The cone of influence was determined to identify the time interval in which any frequency can be considered reliable. Moreover, we evaluated a background noise spectrum for the significance of the GWPS peaks, and the 95 $\%$ significance levels for the WPS; typically we assumed a red noise spectrum because it is higher than the white one, especially with respect to low frequencies.

III. Results and discussion

We firstly found pronounced peaks in the GWPS in the range 2-4 yr when analyzing the NSO/KP photospheric field, averaged between -40°/+40°. By filtering the original signal with a pass band filter (54.16 d-5 yr) we identified it again, though having eliminated lower frequencies peaks in the GWPS. Hence, it seems very improbable that QBOs could be a spurious peak caused

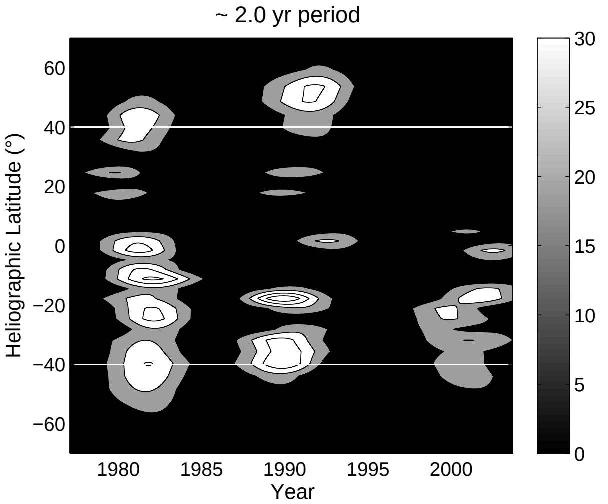

Fig. 2: Wavelet power to red noise significance level (95%) of the NSO/KP magnetic field for the ∼2.0 yr period as a function of time and the central heliographic latitude.

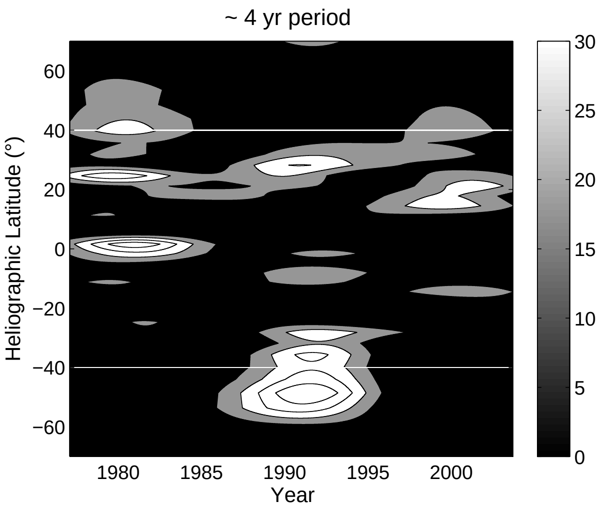

Fig. 3: As in figure 1 for the ∼4.0 yr period.

by the presence of long trends in the data series. A less definite peak at a slightly different value of $2.11^{+0.20}_{-0.19}$ yr was also found in the magnetic field data averaged over all latitudes. That could indicate that QBOs are characteristic only of the active latitudes. Indeed, when performing the analysis at all solar latitudes (Figure 1), we detected the maximum global power in the period range 2-4 yr, particularly at middle latitudes. Moreover, we note that in the GWPS the dominant period is ~ 2 yr for the Southern hemisphere, while it is shifted at ~ 4 yr in the Northern one.

It is worthwhile to recall that the wavelet procedure allows to gain information on the time behaviour of each oscillation. Figure 2 and 3 show the trend of ratio between the the WPS and the 95% red noise significance level for the ~ 2 yr and ~ 4 yr, respectively, as a function of latitude and time. Notice that when this

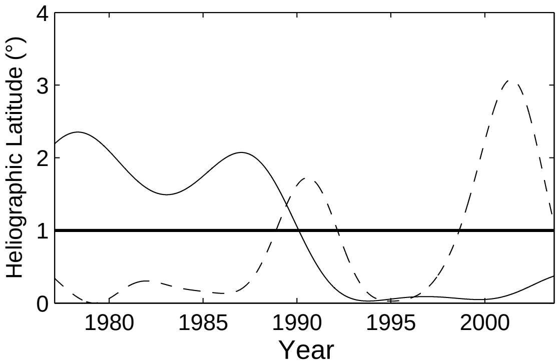

Fig. 4: Wavelet power, normalized to the 95% significance level, versus time for the $3.93^{+0.36}_{-0.34}$ yr (solid line) and $2.05^{+0.09}_{-0.08}$ yr (dashed line) periodicities found for the sunspot area in the Northern and Southern hemisphere, respectively.

ratio is greater than 1, the QBO power is significant. Let us focus on the latitude belt $-40°/40°$, where it is concentrated the bulk of the solar sources associated to the most energetic events, with particular regard to solar energetic particle (SEP) events. Figure 2 shows that the ~ 2 yr period is present at the solar equator and in the Southern hemisphere in all the considered solar cycles, although it is more intense in cycle 22 in the heliographic latitude range $-46°/-16°$ (where a greater number of isocontours is present). On the other hand, it is almost absent in the Northern hemisphere throughout the whole analyzed time interval. The opposite trend is displayed in Figure 3 for the ~ 4 yr oscillation. It has always noticeable power in the Northern hemisphere during the three cycles, especially in cycle 21. In the Southern hemisphere it appears only during cycle 22, although with lower power respect to the ~ 2 yr one.

A similar result is shown in Fig 4, when the wavelet analysis is applied to the sunspot area data set. In fact, a $3.93^{+0.36}_{-0.34}$ yr period was recognized as a strong peak in the GWPS in the Northern hemisphere. On the other hand, it lacks in the GWPS computed for sunspot area in the Southern hemisphere, where a peak at $2.05^{+0.09}_{-0.08}$ is found. When considering their wavelet power as a function of time (Figure 4), we notice that the $3.93^{+0.36}_{-0.34}$ yr period is only effective in cycle 21, whereas the $2.05^{+0.09}_{-0.08}$ in cycles 22 and 23, consistently with results from the magnetic field data.

Finally, we report in the upper panel of Figure 5 the normalized power vs time of the $3.76^{+0.17}_{-0.16}$ periodicity (consistent within the uncertainties with the $3.93^{+0.36}_{-0.34}$ of the sunspot area), found to be a characteristic variation of P2 and P11 proton fluxes (see [13]). In the bottom panel it is displayed the time evolution of the 2.23 yr and 1.7 yr periodicities, detected as strong peaks in the GWPS of P2 and P11 data, respectively. Again, we notice that the solar cosmic ray flux is modulated by a ~ 4 yr period during solar cycle 21 and by a ~ 2 yr period during cycle

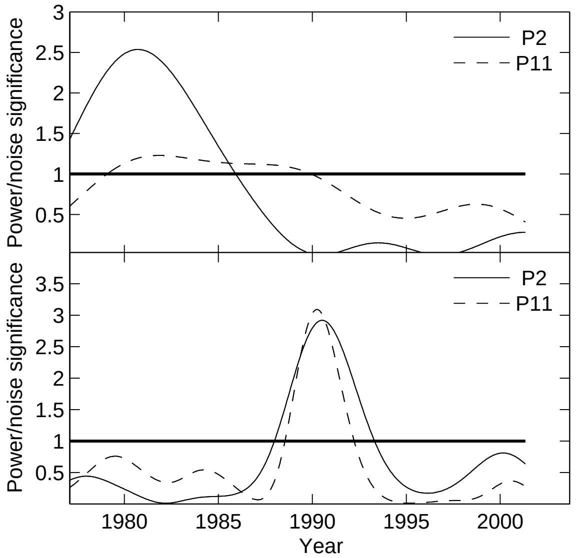

Fig. 5: Wavelet power, normalized to the 95% significance level, versus time for different periodicities of P2 and P11 proton fluxes, after applying upper cutoff (1500 pfu for P2 and 3×10^{-3} pfu for P11). (top) ~ 4 yr periodicity. (bottom) ~ 2 yr periodicity.

22. Given the relationship between the solar magnetic field and the production of solar energetic particles, we argue that the variability of SEP fluxes is essentially determined by the evolution of the magnetic field in the Northern (Southern) hemisphere in cycle 21 (cycle 22). This interpretation is consistent with past findings about the North-South asymmetry exhibited by many solar phenomena. In particular, Ref [23] examined relative sunspot numbers as well as sunspot areas and found that the N-S asymmetry favors the Northern hemisphere in the period 1947-1984. On the other hand, the asymmetry during cycle 22 was found to be in favor of the Southern hemisphere for different manifestations of solar activity, such as sunspot groups, active prominences/filaments and both H_α and X-ray flares of class M≥ 1 (e.g. [24], [25]), to which SEP events are usually associated.

IV. CONCLUSIONS

We confirm that the predominant periodicity in all the considered data sets, is close to ~ 4 yr in cycle 21 and shifts to ~ 2 yr in cycle 22. Moreover a North - South asymmetry was found in the variability of the solar magnetic field and the sunspot areas. Thus, we suggest that the modulation of the solar energetic proton flux is associated with the evolution of the solar magnetic field in the Northern hemisphere during cycle 21 and with that in the Southern one during cycle 22.

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