Geofísica Internacional (2004), Vol. 43, Num. 2, pp. 251-257

Heliospheric consequences of solar activity in geophysical and interplanetary phenomena

J. F. Valdés-Galicia, A. Lara and D. Maravilla
Instituto de Geofísica, UNAM, México

Received: March 31, 2002; accepted: July 18, 2002

RESUMEN

Hemos hecho un análisis de diversos fenómenos solares como el flujo magnético solar total, el área de los hoyos coronales polares y las manchas solares. Investigamos su evolución temporal a lo largo de varios ciclos solares y su posible relación con ondas de choque interplanetarias, comienzos repentinos de tormentas magnéticas en la Tierra y variaciones en la intensidad de rayos cósmicos. Nuestros resultados enfatizan la relación entre la emergencia de flujo magnético solar y la dinámica del medio interplanetario, en particular la importancia de la evolución de los hoyos coronales y la estructura de la heliosfera.

PALABRAS CLAVE: Flujo magnético, hoyos coronales, heliosfera.

ABSTRACT

We have done an analysis of the total solar magnetic flux, polar coronal hole area and sunspots. We investigate their long term evolution over several solar cycles and their possible relationship with interplanetary shocks, sudden storm commencements at earth and cosmic ray variations. Our results stress a physical connection between solar magnetic flux emergence and interplanetary medium dynamics, in particular the importance of coronal hole evolution in the structuring of the heliosphere.

KEY WORDS: Magnetic flux, coronal holes, heliosphere.

INTRODUCTION

The emergence, transport and interaction of magnetic flux at the surface of the Sun is reflected in the solar atmosphere through the evolution of coronal holes and coronal mass ejections (CMEs). The accumulated magnetic flux and stresses may be transported out of the corona via the CMEs. The fastest of these produce interplanetary shocks. Shelley *et al.* (1985) found that 72% of the shocks observed by Helios 1 were associated with large low-latitude CMEs observed by Solwind; most of the CMEs had velocities in excess of 500 km s^{-1}. The shocks reaching the Earth produce Sudden Storm Commencements (SSC) with a 80-90% probability as was demonstrated by Smith *et al.* (1986).

As regions of open flux, it is evident that coronal holes are major participants in the removal of magnetic flux from the Sun. If in fact CMEs are removing magnetic flux from the corona and they do not suffer strong modifications in the interplanetary medium, it is reasonable to expect a similar temporal evolution among magnetic flux emergence, coronal hole area, CMEs, and SSCs.

Cosmic rays are energetic charged particles arriving to the heliosphere. Cosmic ray transport is largely affected by the dominant heliospheric structures which in turn are modified by solar phenomena. Therefore the temporal evolution of those solar phenomena that are the most influential in the heliosphere should determine some of the observed temporal variations in cosmic ray intensity.

The purpose of this work is to review and reassess previous results of our group (Mendoza *et al.*, 1999, Maravilla *et al.*, 2001) dedicated to analyse the temporal behaviour of several solar and interplanetary phenomena, and discuss its relevance in a more general context under the light of new cosmic ray and solar wind fluctuations found recently (*e.g.,* Mursula and Zieger, 2000, Kudela *et al.*, 2002).

DATA AND ANALYSIS

In our analysis we used:

1. The total magnetic flux for each Carrington rotation derived from the National Solar Observatory/Kitt Peak full disk magnetograms for the years 1975-1996 (solar cycles 21 and 22) (Harvey, 1994).

2. The total monthly number of interplanetary shocks observed by Helios 1 for the years 1974-1986, corresponding to cycle 21 (Khalisi, 1996).

3. The monthly numbers of SSCs from 1868-1996 spanning solar cycles 11 to 22 (Solar Geophysical Data).

4. Green corona low-brightness (GCLBR) regions from 1939-1996 (cycles 18-22) as proxys of coronal hole area. This relation was established since the times of Skylab and has been confirmed later on by many authors (see, *e.g.* Dorotovič, 1996). GCLBR are depletions in the Fe XIV (5303 A) emission line above the solar limb. Although there could be other frequency bands better suited to study coronal holes, *e.g.*, soft X-rays, we do not have long term observations at these frequencies.

5. The sunspot number series for cycles 18-22, that we use mainly as a reference of a phenomenon well imbedded in the photosphere and whose evolution is certainly linked to coronal holes and magnetic flux emergence.

These five data series are plotted in Figures 1 and 2.

As it has better frequency resolution the Maximum Entropy Method (MEM) (Burg, 1975) was used to compute the Power Spectral Densities (PSD) of the time series. The basic idea of the MEM is as follows: the PSD is defined as the Fourier transform of the autocorrelation sequence

$$P_{xx} = T \sum_{m=-\infty}^{\infty} r_{xx}(m) \exp(-2 j \pi m T) \quad ,$$

where P_{xx} is the *PSD* at frequency *f*, *T* is the period, r_{xx} is the autocorrelation at lag *m* and $j = (-1)^{1/2}$.

As we never have the entire autocorrelation sequence (ACS) to compute the actual PSD, it is necessary to design methods to get a good approximation to the real PSD. The approximation we use here is that of Burg(1975), who suggested an extrapolation in such a way that the entropy of the time series represented by an extrapolated ACS becomes maximum.

The MEM became popular because it has a better frequency resolution, particularly for short data series, such as the sub-series (one solar cycle length) that we are studying, compared with other methods like, e.g., the periodogram method. A detailed treatment of the MEM can also be found in Ulrich and Bishop (1975) and Burhstein and Weinstein (1987).

To calculate the level of confidence of the PSD the original data of each series was mixed randomly to create a noise time series (NTS). The process is repeated fifty times and the respective PSD calculated. The noise level is then the mean of all the NTS-PSD. The dashed horizontal lines in Figures 3 to 6 represent the 95% and 68% levels of confidence estimated by this procedure. This method is frequency dependent and underestimates the errors at low frequencies. Nevertheless, as we shall see below, our results show that the low frequency peaks are always well above the calculated confidence levels, thus their existence is beyond any doubt.

To filter out the contribution of the highest frequencies we have applied a 7 month running average to the series. As the 11y peak was highly dominant in the magnetic flux, shocks and SSC data and would obscure any possible analysis of the relative importance of the remaining PSD peaks, we also filtered out that contribution in the respective series.

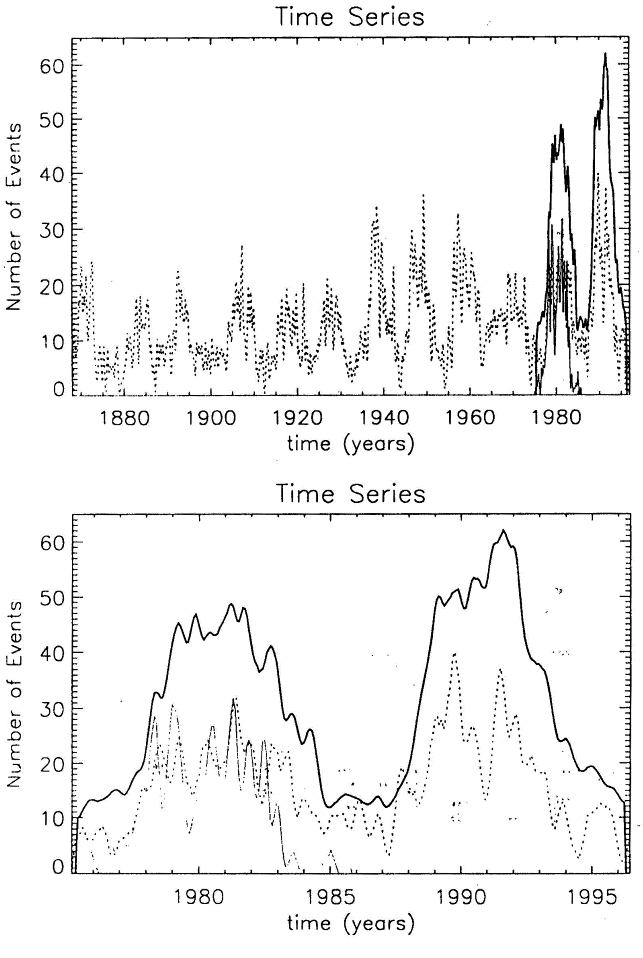

Fig. 1. Upper panel: Total magnetic flux for Carrington rotation for the years 1975-1996 (Carrington rotations 1625-1910) (thick solid line). Monthly number of interplanetary shocks observed by Helios 1 for the years 1974-1986 (thin solid line). Monthly number of SSCs for the years 1868-1996 (points). Lower panel: Enlargement of solar cycles 21 and 22 with the same information as the upper panel.

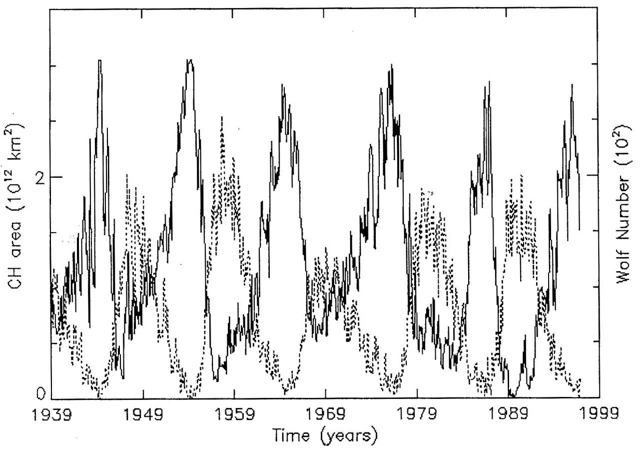

Fig. 2. Monthly polar coronal hole area (thick line) and monthly sunspot number (dotted line) time series for the years 1939-1996. The coronal hole area is computed using the green corona low-brightness regions (GCLBR).

RESULTS AND DISCUSSION

In Figures 3 to 6 we present results of PSD calculations for each one of the five data series used. Figure 3 presents the calculations of magnetic flux for cycles 21 and 22. The shock list for Helios 1 included only cycle 21, estimates of their PSD are presented in Figure 4. In Figure 5 we include the spectral calculations for SSC for cycles 21 and 22. We present results of the analysis of the separate cycles as well as those for cycles 21 and 22 together in order to see which features remain over a complete 22y solar cycle and whose are particular of one of them only, in search for clues that could also indicate differences between even and odd solar activity cycles. Figure 6 shows the PSD of coronal hole area and sunspots for cycles 18 to 22.

Tables 1 to 3 are a summary of the results presenting the most significant peaks obtained with their related uncertainties that are calculated as the widths of the corresponding peak at half maximum. All the periodicities appearing in Tables 1 to 3 are significant to at least 68% level of confidence.

We will concentrate here in the main results of the spectral analysis that was not discussed previously as evidence published recently provides a more general context for the discussion and a path for reassessment of its possible consequences.

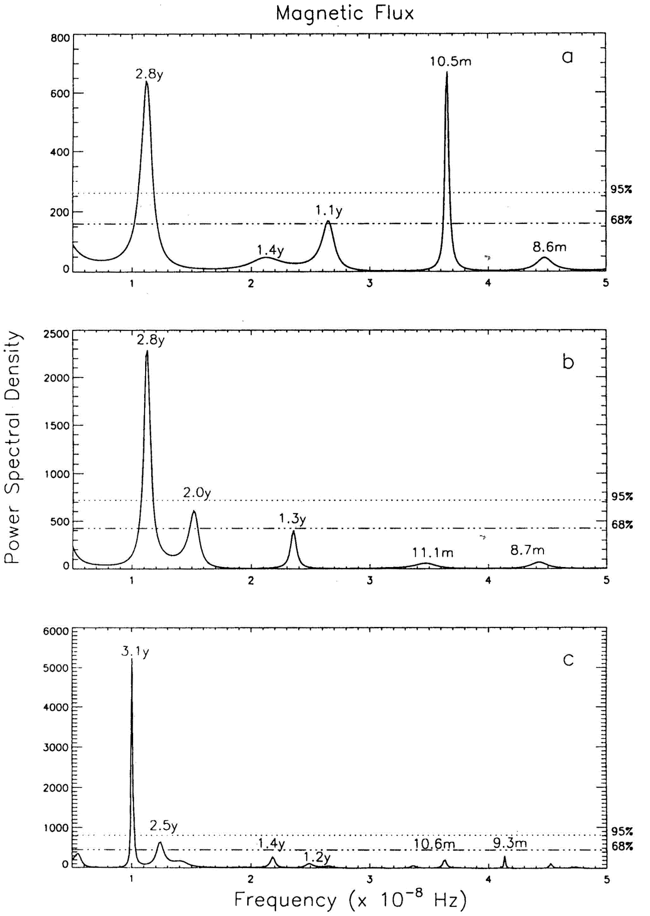

Fig. 3. Magnetic flux PSD. (a) For cycle 21. (b) For cycle 22. (c) For cycles 21+22.

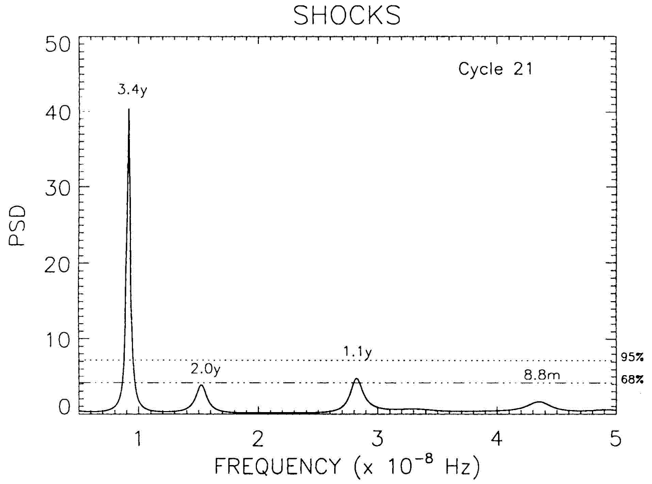

Fig. 4. Interplanetary shock PSD for cycle 21.

One of our most important findings is the existence of a quasi triennial fluctuation present in all the phenomena analysed. The fluctuation tends to be closer to three years in magnetic flux emergence and sunspots while the spectral peak for coronal holes and interplanetary phenomena (SSCs and shocks) is shifted to 3.5 years. This might be an indication that magnetic flux emergence periodicity of 3 years could

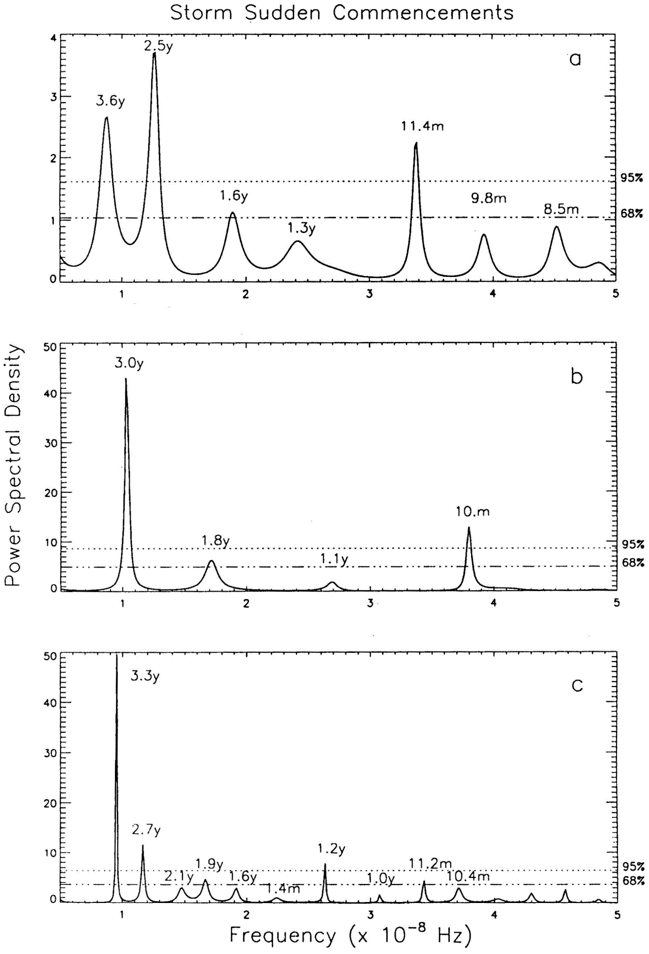

Fig. 5. Storm sudden commencements PSD. (a) For cycle 21. (b) For cycle 22. (c) For cycles 21+22.

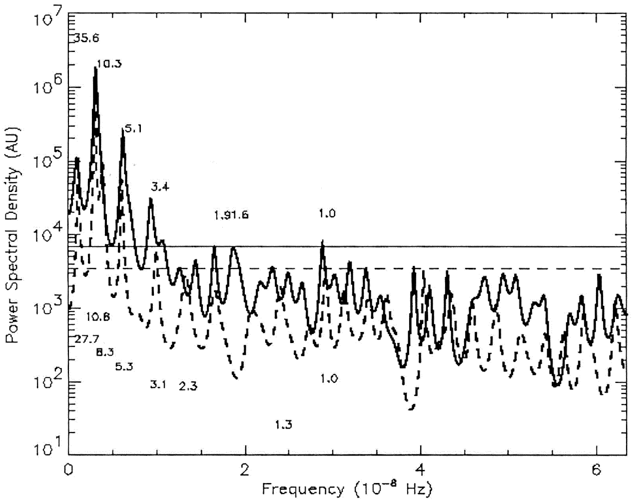

Fig. 6. PSD for coronal hole area (solid line) and sunspot number five cycle series (dashed lines).

have a predominant role in sunspot dynamics (inner atmosphere) while coronal holes (outer atmosphere) evolution has a closer connection to interplanetary medium phenomena. A shifted quasi triennial fluctuation in cosmic rays was also found by Valdés-Galicia *et al.* (1996) in a four solar cycle period. We should point out that the dominant peak of the PSD of the SSCs is closer to four years in the whole data set (cycles 11 to 22) as compared to 3 years in cycles 21 and 22. This may be a consequence of a longer term solar cycle or an unfolding of the 4 yr period. Three year periodicities were reported in meridional flows identified trough sunspots, magnetic features and Doppler shifts data (Valdés-Galicia and Mendoza, 1998, Snodgrass and Dailey, 1996, LaBonte and Howard, 1982). These meridional flows are certainly connected with the convective solar motions and therefore with the emergence of magnetic flux to the solar surface.

Non negligible variations of around 1.6 to 1.9 y are present in SSCs and coronal holes but not in sunspots or solar magnetic flux. This fluctuation was found to be dominant in cosmic ray intensity time series for four solar cycles where a low pass filter was applied to remove the 11y periodicity (Valdés-Galicia *et al.*, 1996). Recently Kudela *et al.* (2002) confirmed the existence of this fluctuation using a different cosmic ray intensity time series and a different method to calculate the PSD. Kudela *et al.* (2002) found also that, while the ~1.7y cosmic ray variation is present in every solar cycle, a periodicity of 1.3y appears and is dominant in even cycles. If alternating periodicities are a systematic feature of consecutive cycles in cosmic ray modulation, it enhances the relevance of the differences found between even and odd solar cycles (see *e.g.,* Storini, 1997, Bazilevskaya *et al.*, 2000). In fact this alternation is also observed in coronal hole area evolution (Maravilla *et al.*, 2001), hence active region locations should also exhibit an alternating behavior. An additional evidence pointing in the direction indicated are the recent findings of Mursula and Zieger (2000). These authors identified a 1.3y fluctuation in solar wind velocity for even solar cycles that tends to longer periodicities (1.6-1.7y) during odd cycles.

Certainly more work is needed on this subject to clarify the detailed causal relations between solar and interplanetary phenomena analysed. Nevertheless, at this point we can state that all the referred results taken together strongly suggest that coronal hole evolution restructures the whole heliosphere influencing the transport of interplanetary phenomena and cosmic rays and, as a consequence, the rate at which important geomagnetic phenomena occur.

A long term variation of around 30y is present in coronal holes and sunspots. It deserves some attention as it was identified in several phenomena: Silvermann(1992) found a 33.3yr peak in a power spectrum done for sunspots between 1868 and 1990. Clua de Gonzalez *et al.* (1993) also

Table 1

Significant peaks (in years) for magnetic flux (MF), shocks (Sh), and sudden storm commencements (SSC)

	Cycles 11 to 22	**Even Cycles**	**Odd Cycles**	**Cycles 21+22**	**Cycle 21**	**Cycle 22**
MF				3.1 ± 0.1^{b}	2.8± 0.4^{b}	2.8± 0.2^{b}
				2.5 ± 0.2^{c}	10.5± 0.2^{a,b}	2± 0.2^{c}
					1.1± 0.1^{c}	1.3±0.4^{c}
Sh					3.4± 0.2^{b}	
					1.1±0.2^{c}	
					2.0±0.2^{c}	
SSC	3.8± 0.3^{b}	1.8± 0.1^{b}	4.1± 0.2^{b}	3.3 ± 0.1^{b}	2.5± 0.3^{b}	3± 0.1^{b}
	2.4± 0.1^{c}	3.8± 0.2^{b}	3.8± 0.2^{b}	2.7± 0.1^{b}	3.6 ± 0.6^{b}	10± 0.2^{a,b}
	1.7± 0.1^{c}	1± 0.1^{b}	2.4±0.2^{c}	1.2± 0.1^{b}	11.4± 0.3^{a,b}	1.8±0.2^{c}
	2.7±0.1^{c}	3± 0.4^{b}	10±0.2^{a,c}	1.9±0.3^{c}	1.6± 0.2^{c}	
	4.5±0.3^{c}	1.4±0.2^{c}	11.2±0.2^{a,c}	11.2±0.2^{a,c}	11.4±0.3^{a}	

(a) time variations in months; (b) 95% level of confidence; (c) 68% level of confidence

Table 2

Significant peaks of coronal holes

Cycle

18	*19*	*20*	*21*	*22*	**All**
					35.6±6.14
10.3±0.22	9.5±0.23	11.8±0.2	10.8±0.46	10.3±0.50	10.3±0.43
4.8±0.06	5.3±0.15	5.8±0.06	4.6±0.07	4.9±0.21	5.1±0.12
3.1±0.03	3.7±0.18	3.7±0.02		3.0±0.07	3.4±0.06
		2.4±0.01	2.3±0.01		
1.7±0.01	2.0±0.01	1.8±0.001		1.8±0.02	1.9±0.01
					1.6±0.03
1.4±0.01	1.2±0.002			1.4±0.02	
0.97±0.05	1.0±0.007		0.95±0.07		1.0±0.002

Table 3

Significant peaks of sunspots

Cycle

18	*19*	*20*	*21*	*22*	**All**
					27.7±1.7
10.3±0.17	10.8±0.28	11.3±0.20	10.0±0.16	10.3±0.50	10.8±0.19
4.7±0.06	6.2±0.07	5.8±0.08	4.8±0.29		5.3±0.08
	3.2±0.01		2.9±0.07	2.8±0.04	3.1±0.04
		2.5±0.02			2.3±0.05
2.0±0.05		1.8±0.004	1.9±0.01	2.0±0.03	
1.3±0.01	1.4±0.001		1.1±0.001		
1.0±0.004	0.95±0.04			1.0±0.005	1.0±0.001

report a 30y periodicity in sunspots for the period 1932-1982, although it does not appear in the interval 1920-1982. Monthly auroral occurrence present a 33.3y peak over the period 1500-1948 with an irregular appearance. The planetary index Ap also shows this periodicity for the interval 1932-1997 (Ahluwalia, 1998), but it is not present in the interval 1866-1931 (Wilson and Hataway, 1999). SSCs present a 26.2yr fluctuation in the period 1939-1996, which appears closer to 20y during 1932-1982 and 1868-1996 (Mendoza *et al.*, 2002). Therefore it seems that a periodicity of around 30yr exists in the Sun and this is reflected in interplanetary and geophysical phenomena but its appearance is unstable and does not allow to predict when it will be present in the data or speculate about possible mechanisms that may produce it.

SUMMARY AND CONCLUSIONS

1. The 1.6±0.2-y fluctuation is a well established feature in cosmic ray intensity and interplanetary phenomena (Valdés-Galicia *et al.*, 1996, Mursula *et al.*, 2000, Kudela *et al.*, 2002). Circulation of solar features that imply magnetic flux transport have characteristic times in the same range. Therefore this fluctuation might be related to the solar convection. To make a more definitive statement we would

need better estimates of the solar meridional motions that reduce the high uncertainties that they have nowadays.

2. The 1.6±0.2-y is also a periodicity present in coronal hole area evolution. This is an indication of the importance of coronal hole dynamics in the structuring of the whole heliosphere.

3. The Sun presents an alternating behavior between even and odd cycles of activity that is manifested in particular in the relative importance of the 1.6y with respect to a 1.3y fluctuation appearing as dominant in even cycles in cosmic ray intensity and solar wind velocity variations.

4. The quasitriennial periodicity found in all the phenomena studied tends to be shifted towards lower frequencies in coronal holes, interplanetary and geophysical phenomena and in cosmic rays with respect to other solar activity indicators. This reinforces the importance of coronal holes in heliospheric dynamics.

5. A 30-y fluctuation exists in the solar atmosphere and geophysical phenomena. Further studies with long datasets are needed.

BIBLIOGRAPHY

AHLUWALIA, H. S., 1998. The predicted size of cycle 23 on the Inferred Three-Cycle Quasi Periodic of the Planetary Index Ap. *J. Geophys. Res. 103,* 12103-12109.

BAZILEVSKAYA, G. A., M. V. KRAINEV, V. S. MAKHUMTOV, E. O. FLUKIGER, A. I. SLADKOVA and M. STORINI, 2000. Structure of the maximum phase of solar cycles 21 and 22. *Solar Phys., 197,* 157-174.

BURG, J. P., 1975. Ph.D. Dissertation, Department Of Geophysics, Stanford University.

BURHSTEIN, D. and E. WEINSTEIN, 1987. Confidence intervals for the maximum entropy spectrum. IEEE trans on acoustics, speech and signal processing, 35 (4), 504-510.

CLUA DE GONZALEZ, A. L., W. D. GONZALEZ, S. L. G. DUTRA and B. T. TSURUTANI, 1993. Periodic variations in the Geomagnetic Activity: A study based on the Ap Index. *J. Geophys. Res. 98,* 9215-9231.

DOROTOVIC, I., 1996. Area of polar coronal holes and sunspot activity. *Solar Phys., 167,* 419-426.

HARVEY, K. L., 1994. *In:* R. J. Rutten and C. J. Schrijver eds. Solar Surface Magnetism, Kluwer Ac. Publ., Netherlands, 347.

KHALISI, E., 1996. Diplomarbeit, Max-Planck- Institut für Aeronomie, Katlenburg-Lindau.

KUDELA, K., J. RYBAK, A. ANTALOVÁ and M. STORINI, 2002. Time evolution of low-frequency periodicities in cosmic ray intensity. Solar Phys., 205, 165-175.

LA BONTE, B. J. and R. F. HOWARD, 1982. Solar rotation measurements at Mount Wilson. *Solar Phys. 80*, 361-372.

MARAVILLA, D., A. LARA, B. MENDOZA and J. F. VALDÉS-GALICIA, 2001. An analysis of polar coronal hole evolution: Relations to other solar phenomena and heliospheric consequences. *Solar Phys., 203,* 27-38.

MENDOZA, B., A. LARA, D. MARAVILLA and J. F. VALDÉS-GALICIA, 1999. Magnetic flux emergence and geomagnetic activity, a close correlation. *Solar Phys., 185,* 405-416.

MENDOZA, B., J. F. VALDÉS-GALICIA, A. LARA and D. MARAVILLA, 2002. Spectral analysis results for sudden storm commencements 1868-1996. *Adv. Sp. Res., 31,* 1075-1079.

MURSULA, K. and B. ZIEGER, 2000. The 1.3 year variation in the solar wind speed and geomagnetic activity. *Adv. Sp. Res., 25(9),* 1939-1942.

SHELLEY, N. R., R. A. HOWARD, M. J. KOOMEN and D. J. MICHELS, 1985. Coronal mass ejections and interplanetary shocks. *J. Geophys. Res., 90,* 163-175.

SILVERMAN, S. M., 1992. Secular variation of the Aurora for the Past 500 years. *Rev. Geophys. 30,* 333-351.

SMITH, E. J., J. A. SLAVIN, R. D. ZWICKL and S. J. BAME, 1986. In Solar Wind Magnetosphere Coupling, Terra. Sci. Publ. Co. Tokyo, p. 345.

SNODGRASS, H. B. and S. B. DAILEY, 1996. Meridional motions of magnetic features in the solar photosphere. *Solar Phys. 163*, 21-42.

STORINI, M., 1997. Cosmic rays for solar-terrestrial physics. *Il Nuovo Cimento, C20,* 871-880.

ULRICH, T. J. and T. N. BISHOP, 1975. Maximum entropy spectral analysis and autoregressive decomposition. *Rev. Geophys. and Sp. Phys., 13,* 183-200.

VALDÉS-GALICIA, J. F. and B. MENDOZA, 1998. On the role of large-scale solar photospheric motions in the cosmic-ray 1.68 yr intensity variation. *Solar Phys. 178,* 183-191.

VALDÉS-GALICIA, J. F., R. PÉREZ-ENRÍQUEZ and J. A. OTAOLA, 1996. The cosmic-ray 1.68 year variation: A clue to understand the nature of the solar cycle? *Solar Phys. 167,* 409-417.

WILSON, R. M. and D. H. HATHAWAY, 1999. The predicted size of cycle 23 based on the Inferred Three-Cycle Quasi-Periodicity of the Planetary Index Ap. *J. Geophys. Res., 104,* 2555-2558.

J. F. Valdés-Galicia, A. Lara and D. Maravilla
Instituto de Geofísica, UNAM, México
Email: jfvaldes@tonatiuh.igeofcu.unam.mx