SOLAR-CYCLE PHENOMENA IN COSMIC-RAY INTENSITY: DIFFERENCES BETWEEN EVEN AND ODD CYCLES

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(Received 28 April, 1988)

Abstract. Cosmic-ray intensity data for the period 1964–1985 covering two solar cycles are used to investigate the solar activity behaviour in relation to cosmic-ray modulation. A detailed statistical analysis of them shows a large time-lag of about one and half years between cosmic-ray intensity and solar activity (as indicated by sunspot number, solar flares and high-speed solar-wind streams) during the 21st solar cycle appearing for a first time. This lag indicates the very high activity level of this solar cycle estimating the size of the modulating region to the unambiguous value of 180 AU. The account of the solar-wind speed in the 11-year variation significantly decreases the modulation region of cosmic-rays to the value of 40 AU.

A comparison with the behaviour of the previous solar cycle establishes a distinction between even and odd solar cycles. This is explained in terms of different contributions of drift, convection and diffusion to the whole modulation mechanism during even and odd solar cycles.

1. Introduction

It is known that the solar activity presents many strange characteristic features from cycle to cycle and have been examined in detail from several researchers. For example Legrand and Simon (1985) have noted that there are series of cycles with very high activity level (cycles 18, 19, etc.) as well as quite low activity (cycles 5, 6, 12 and 14). Xanthakis *et al.* (1981) have showed that the amplitude of solar modulation in the 20th solar cycle was smaller than the corresponding one of the 19th solar cycle.

On the other hand a number of studies have shown that the long-term variation of galactic cosmic-ray intensity over a solar cycle bears a close inverse relationship to the actual solar activity cycle (Forbush, 1958; Pomerantz and Duggal, 1974; Moraal, 1976; Mavromichalaki and Petropoulos, 1984). The sunspot number or/and the flare activity have been used by many authors in order to simulate the cosmic-ray intensity from the solar activity (Křivský, 1977; Hatton, 1980). Recently an attempt was made to find the most suitable index of the solar activity in order to reproduce to a certain degree the modulation of the cosmic-ray intensity (Nagashima and Morishita, 1980). The contribution of more than one solar, interplanetary or geophysical parameter to the cosmic-ray modulation process as solar flares, sunspot number, proton events, geomagnetic index, etc., have been also reported (Mavromichalaki and Petropoulos, 1987). So examining the pattern of cosmic-ray modulation with respect to the most suitable solar, interplanetary and geophysical parameters we can investigate the characteristic phenomena of the solar activity during a solar cycle.

An anomalous behaviour of the cosmic-ray intensity during the different solar cycles has also been described by several authors. This can be characterized by the

Earth, Moon, and Planets **42** (1988) 233–244.

abnormality of the modulation rigidity spectra of cosmic-ray intensities (Lockwood and Webber, 1979), the softening of the spectra (Garcia-Munoz *et al.*, 1977), the poor correlation of the cosmic-ray intensity with the solar activity (Akopian *et al.*, 1981). During the 21th solar cycle a remarkably large time-lag between cosmic-ray minimum which occurred in August 1982 and the sunspot maximum which was in September 1979 has been reported for a first time (Legrand and Simon, 1985).

The purpose of this work is to identify all these characteristic features of this solar cycle in the light of phase lag between cosmic-rays and various kinds of solar, interplanetary and geophysical parameters. It has been shown that the differences between the shapes of the curves representing the variation of these quantities introduce a hysteresis-like phenomenon, which is considerably increased in this solar cycle. The study of this phenomenon as well as other ones related to this happening during the 21st solar cycle, which is an odd cycle, in comparison with the previous solar cycle which was an even solar cycle, led us to establish many substantial differences between even and odd solar cycles.

2. Method of Study

In order to study the long-term cosmic-ray modulation for solar cycle 21st we applied a method of data analysis which appeared by Mavromichalaki and Petropoulos (1984).

So we used neutron monitor data (corrected for pressure) of Inuvik station (Super NM-64, Threshold rigidity 0.18 GV) for the time interval 1965–1985 which were normalized so as the intensities at solar minimum are taken equal to 1.00 and those at solar maximum are taken equal to zero. Also for this analysis monthly values of relative sunspot number (Zürich Observatory), the flares of importance ≥ 1N, the flares of importance ≥ 1B and the geomagnetic index A_P have been used (Solar-Geophysical Data Reports).

For the same period we have found and identified the two categories of high-speed solar-wind streams. The first one is the slow undisturbed wind of 'quiet days' emitted by coronal holes and called 'Corotating' streams.

The second one is the stable high-speed solar-wind streams associated with strong active regions emitting solar flares and producing Forbush decreases in the Earth and so called 'Flare-generated streams' (Burlaga, 1975; 1979; Simon and Legrand, 1986, etc.). The number of solar wind streams is taken by a catalogue given by Mavromichalaki *et al.* (1988) based on a data compilation by J. King, available through the National Space Science Data Center (King, 1979; 1983; 1986a, b)

3. Results

Time-series of semi-annual values of the cosmic-ray intensity, the sunspot number (Zürich number) and the number of solar flares of importance ≥ 1N for the two last solar cycles (20th, 21st) appear in Figure 1. At a first glance it is worth noting

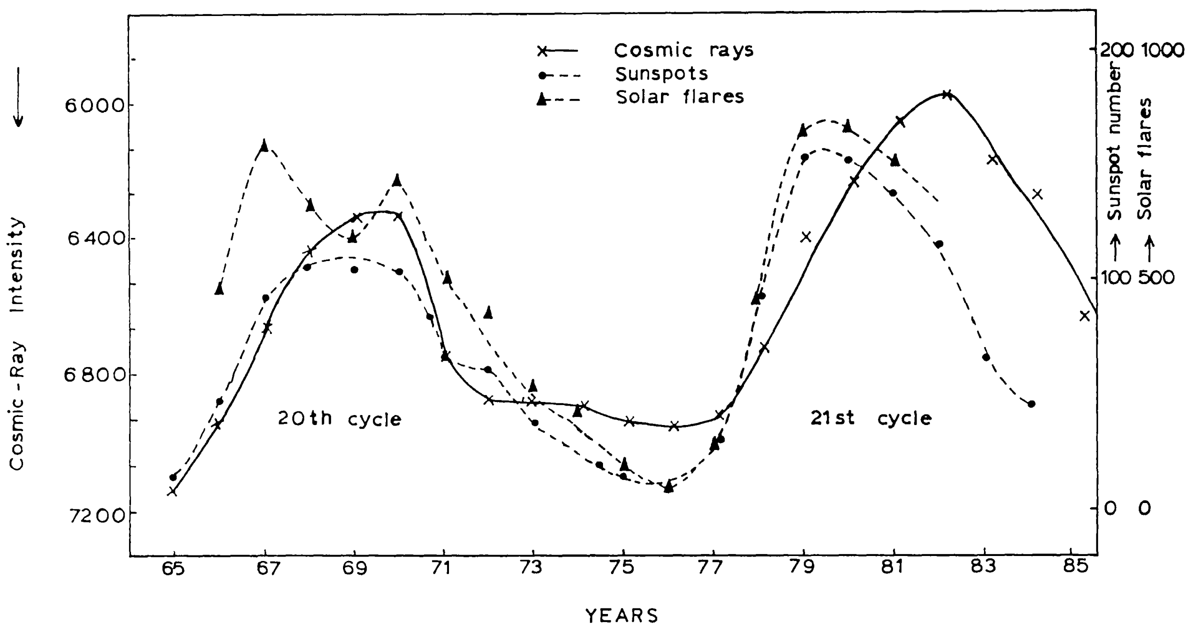

Fig. 1. Cosmic-ray intensity data, relative sunspot numbers and solar flares ≥ 1N during the 20th and 21st solar cycles.

that the sunspot number during the 21st solar cycle is much larger than that of the previous cycle which indicate the high activity level of the last cycle. In contrast, the solar flare activity during the two cycles is about at the same levels. Moreover, the behaviour of the cosmic ray intensity seems to be about the same level during the last two cycles. The differences also between the shapes of the curves representing the variation of the above quantities during these two cycles are obvious. The first cycle is characterized by a saddle-like shape, whereas the other cycle is characterized by a peak-like shape.

On the other hand it is interesting to note the lack of secondary maxima of the above mentioned parameters during the 21st solar cycle in comparison with the previous solar cycles. In addition a large time-lag between the cosmic-ray intensity and each of the other parameters, sunspot number and the number of all occurred flares is obvious from the same figure. Indeed the sunspot maximum occurred in 1979 whereas the cosmic-ray minimum was in 1982, which means about three years delay on the sunspot peak.

A correlating analysis between the monthly mean cosmic-ray intensity and the monthly solar activity (indicated by the sunspot number, the solar flares of importance ≥ 1 and the solar flares of importance ≥ 1B) as a function of the lag of the cosmic-ray intensity with respect to solar activity is carried out. Figure 2 gives the correlation coefficients between the cosmic-ray intensity and the other indices of solar activity for different time lags. We can see that the cross correlation coefficient for the sunspot number is at a maximum for a time-lag of 16 months and for the solar flares of importance ≥ 1N is at a maximum for a time-lag of 17 months, whereas the flares of importance ≥ 1B for a time-lag of six months. It is known that the time-lag between cosmic-ray intensity and solar activity varies from several to 12 months

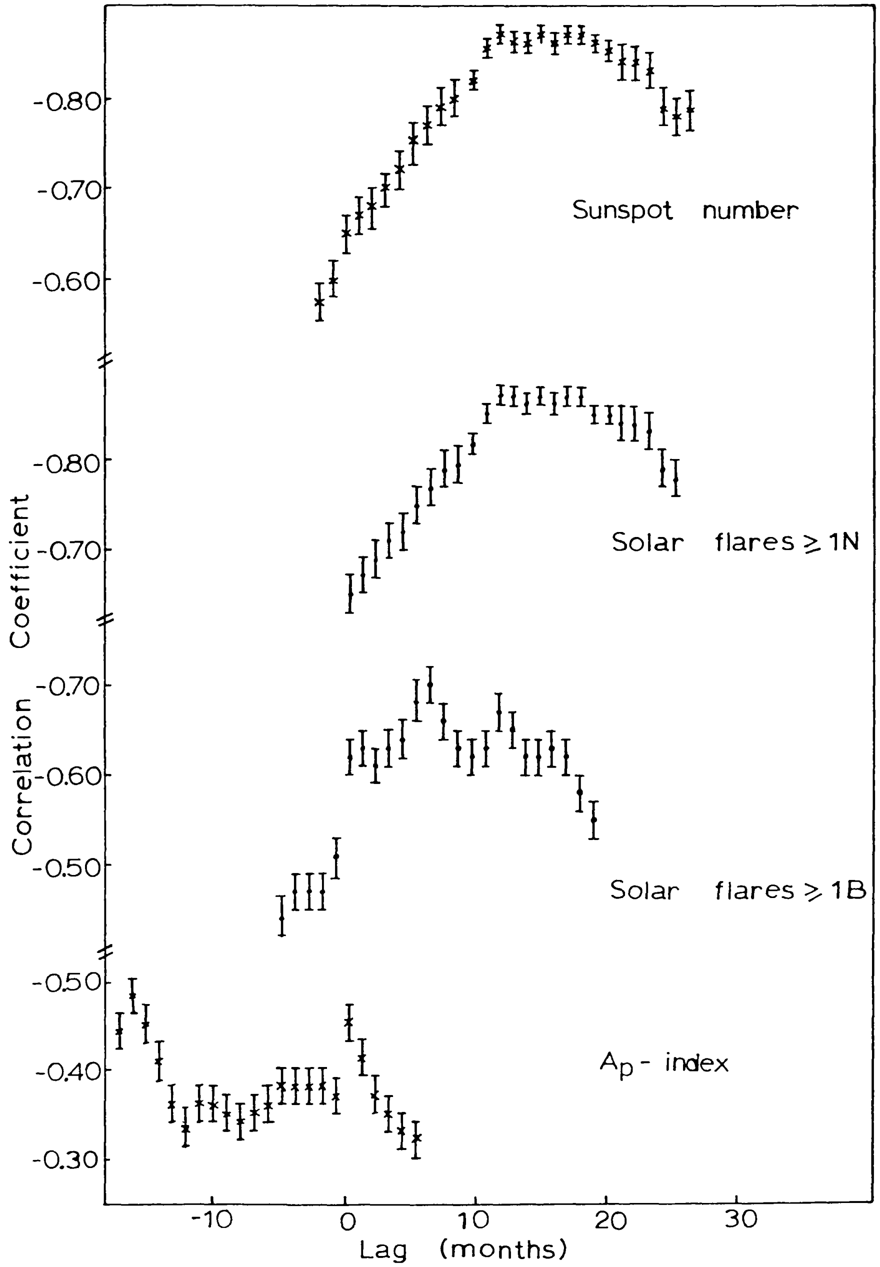

Fig. 2. Correlation coefficient between the monthly cosmic-ray intensity and sunspot number, solar flares ≥ 1N, solar flares ≥ 1B and A_P-index as a function of cosmic-ray intensity lag with respect to these indices for the 21st solar cycle. The statistical errors are indicated.

depending on the solar cycle and the activity index adopted (Dorman *et al.*, 1977; Nagashima and Morishita, 1980a, etc.). The remarkably large time-lag of 17 months between cosmic-ray intensity and solar flares or sunspot number during this solar cycle is observed for a first time. The large hysteresis effect of cosmic-ray intensity during the present cycle was also noted by Legrand and Simon (1985) correlating the cosmic-ray intensity and the shock event activity. The correlation coefficient of cosmic-ray intensity and geomagnetic activity expressed by A_P index does not appear a pronounced maximum. One can distinguish two peaks one at zero months and another one at -16 months. It is consistent with the results of previous solar cycles (Balasubrahmanyan, 1969; Mavromichalaki and Petropoulos, 1984) where the Bartels's A_P index correlates with the cosmic-ray intensity without pronounced phase lags or with two maxima.

The same correlation analysis between monthly cosmic-ray intensity values and the monthly number of high-speed solar-wind streams have been also carried out. The correlation coefficient is maximum when a lag of five months is introduced into the streams data (Figure 3). This is consistent with the time-lag of the most important solar flares $\geq$ 1B which have appeared at a maximum of 6 months. This relatively short lag may indicate that the total influence of the high-speed solar-wind streams on cosmic-ray intensity is limited to smaller regions around the sun. Nevertheless the time-lag of each one of the two categories of the solar wind streams, the corotating

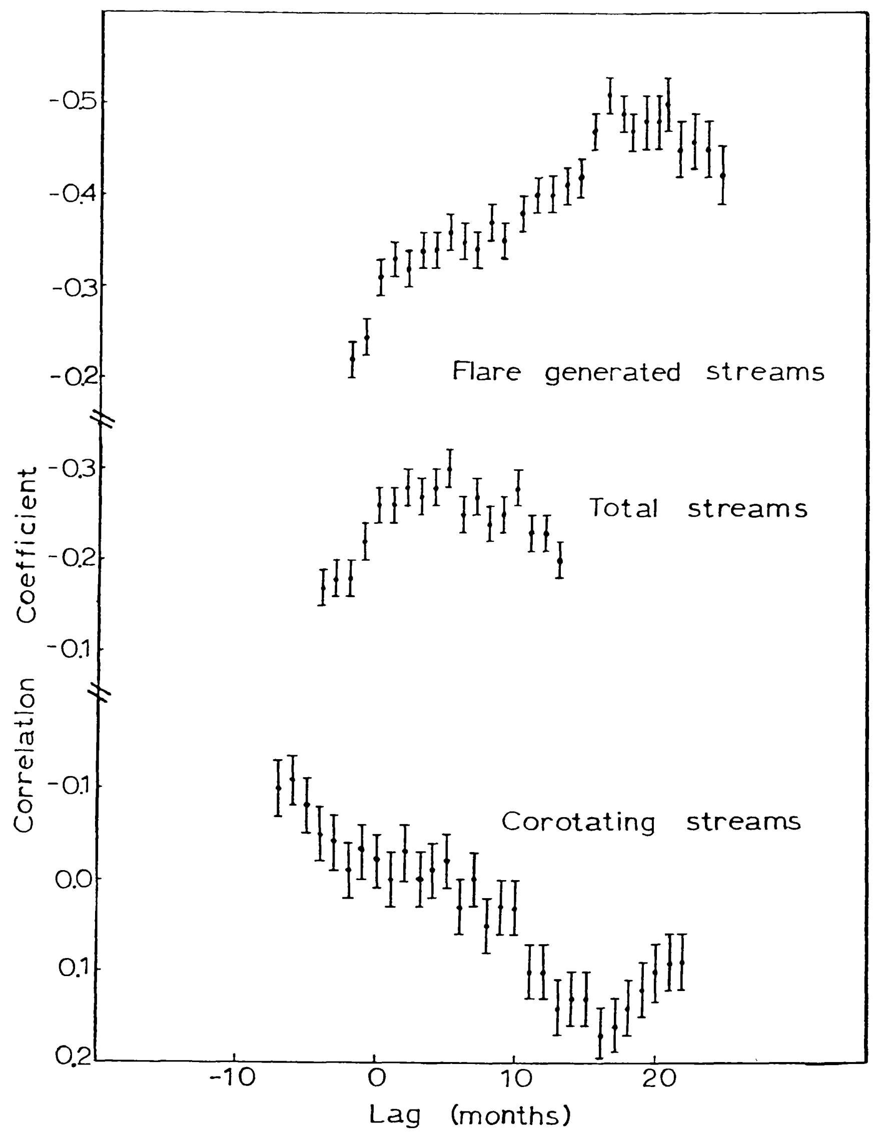

Fig. 3. Correlation coefficient between the monthly cosmic-ray intensity and total number of streams, flare-generated streams and corotating streams as a function of cosmic-ray intensity lag with respect to these indices for the 21st solar cycle. The statistical errors are also indicated.

TABLE I

Cross correlation coefficient and the corresponding time lags for the solar cycles 20 and 21.

	20th cycle		21st cycle	
Indices	r	Lag (months)	r	Lag (months)
Sunspot number	-0.88 ± 0.01	2	-0.87 ± 0.01	16
Solar flares ≥ 1N	-0.76 ± 0.02	4	-0.87 ± 0.01	17
Solar flares ≥ 1B			-0.70 ± 0.02	6
Streams	-0.30 ± 0.02	3	-0.30 ± 0.02	5
Flare-generated streams			-0.51 ± 0.02	16
Corotating streams			-0.17 ± 0.03	16
A_p-index	-0.20 ± 0.02	0	-0.45 ± 0.02	0
	$+0.33 \pm 0.02$	12	-0.48 ± 0.02	16

and the flare-generated streams, appeared the same as the corresponding time-lag of the sunspot number and the solar flares. Moreover the correlation of the cosmic-ray intensity with the flare generated streams is stronger than that with the corotating streams. It means that the flare-generated streams affected mainly the cosmic-ray modulation of the 21st cycle (Legrand and Simon, 1985) and not the corotating streams, as it was believed for the previous cycle (Mavromichalaki and Petropoulos, 1984). This is in agreement with the relatively short time lag of the solar flares ≥ 1B.

The time-lag of cosmic-ray intensity which corresponds to the cross correlation coefficient of each parameter for the cycles 20th and 21st is given in Table I. According to the Fisher's Z-transformation of significance of correlation coefficients we have found that the above estimated correlation coefficients for the data series of cosmic-ray intensity and each of the indices referenced in the Table I, are at a 99% confidence level.

Furthermore we computed the correlation coefficient of the cosmic-ray intensity with all the above parameters for every one year of solar cycle No 20. It is interesting to note that the run of the correlation curve for each parameter presents a periodic variation of two years, as is shown in Figure 4. A small exception from this period appeared in the case of the A_P-index of geomagnetic activity where the correlation coefficient is not following any rule. From this figure we can not observe any relation of this correlation with the solar maxima or solar minima. From previous cycles several authors have shown that this correlation is stronger (negative) during the solar minima than the solar maxima (Simpson, 1963; Mavromichalaki and Petropoulos, 1984).

4. Discussion

The existence of two maxima in the sunspot activity during an 11-yr solar cycle was first shown by Gnevyshev (1967) for the period 1954–1962. He also showed similar

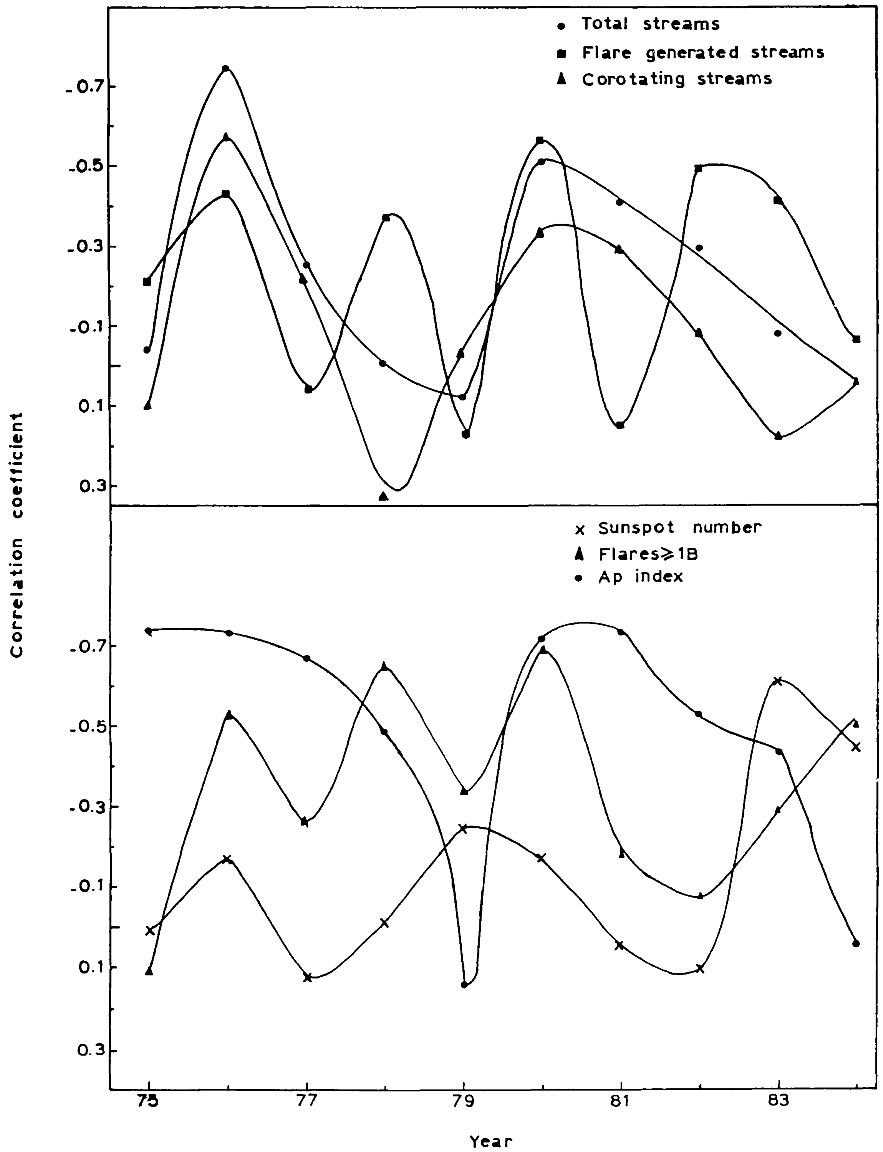

Fig. 4. Yearly correlation coefficient of the cosmic-ray intensity with the sunspot number, the flare ≥ 1B, the A_P-index, the total streams for the 21st solar cycles.

maxima in other indices of solar activity. Later the study of different solar phenomena has confirmed the fact that the 5303 A coronal line intensity which reveals a basic feature of solar activity has indeed two distinct maxima with different physical properties for every 11-y solar cycle (Xanthakis *et al.*, 1982). This solar index can be very well correlated with different solar and terrestrial phenomena that can be present two maxima during a solar cycle such as the distribution of the chromospheric flares (Kopecký, 1973), the number of flares with radio emission II or IV (Dodge, 1975) the Bartel index A_P (Simon, 1979), the intensity of the cosmic radiation (Křivský and Růžičková–Topolová, 1978), etc. Xanthakis *et al.* (1982) have explained the two maxima of the I_{5303} intensity taking into account the evolution of the coronal magnetic field, which can be considered as the result of two components: One due to the poloidal field which exists on the solar surface without any direct relationship to the solar proton events and another due to the convection of the poroidal field into poloidal or radial fields through the formation of proton events and through subsequent penetration of the magnetic field into the corona. Superposition of the two fields can explain the two maxima of the coronal activity.

Recently Otaola *et al.* (1985) have shown that there is a different behaviour of the cosmic ray intensity during even and odd solar cycles which, as it is known, consist of two discrete states each corresponding respectively to the parallel and antiparallel states of polarity of the polar magnetic field of the Sun to the galactic magnetic field. Their analysis shows a tendency towards a regular alternation of cosmic ray intensity cycles with double and single maxima. The shape of the cosmic ray intensity curve of the even cycles differ systematically and markedly from the shape of the odd cycles. The shape of the odd cycle is characterized by a simple and relatively smooth increase to the maximum (7.5 yr) whereas the even cycles on the average are characterized by a two maxima structure in which the first maximum is reached relatively rapid after the previous minimum in the cosmic-ray intensity (3–4 yr) and the second, the main and also more developed tends to occur at the same time in the cycle as the maximum of the odd cycle. They have explained this behaviour in terms of different processes influencing cosmic-ray transport in the heliosphere.

This different behaviour between even and odd cycles is also presented in solar activity (Dodson and Hedeman, 1975) where during even sunspot cycles are characterized by two well defined 'stillstands' in the level of activity during the declining phases of such cycles. Halenka (1983) showed also that the *aa*-index during even solar cycles presents this characteristic while the odd cycles do not. In this work we have also shown that other indices of solar activity such as solar flares and high-speed streams, present the two maxima structure during the 20th cycle while during the 21st cycle does not.

Chirkov and Kuzmin (1979) showed a significant difference of 11-y cosmic-ray variations in even and odd solar activity cycles caused by differences of solar-wind speed in these cycles. This was resulted by a dependence of energy spectrum of 11-y cosmic-ray variations or the sign of the interplanetary magnetic field which in its turn was associated with the total field of the Sun. Nagashima and Morishita (1980) found that the modulation of cosmic-ray intensity is the result of the superposition of the 22-y and 11-y solar modulation. Another characteristic feature of this solar cycle (21st) in relation with the previous one was the large time-lag of cosmic-ray intensity with respect to sunspot number and solar flares $\geq$ 1N. Until now it was known that the time-lag of cosmic-ray intensity with respect to solar activity varies from several to twelve months (Nagashima and Morishita, 1980). Legrand and Simon (1985) correlating the cosmic-ray intensity and the shock event activity, showed that the occurrence of Forbush decreases during the 21st solar cycle is more closely linked to the shock event activity that to the current sunspot number. This is consistent with our result in this work that the solar flares of importance $\geq$ 1B affected mainly the cosmic-ray modulation and not the sunspot number as it was believed. However, if the cosmic-ray modulation is linked as we suggest to the solar flare activity the abundance of Carbon 14 or any other radioactive atom in the Earth atmosphere which is a physical consequence of the flux of the cosmic-ray particles passing through the interplanetary medium should have the same time behaviour as the flare activity, for example: a poor link with the sunspot cycle activity, a very weak cosmic-ray modulation during low activity cycles and an irregular distribution of the modulation during any cycle. This last result is not agreed with the current evaluations of the secular behaviour of the solar activity done according to the observed abundance of C_{14} or any other radioactive atom.

On the other hand this link between the cosmic-ray intensity and the flare activity should explain the irregular shape of the cosmic-ray cycle modulation, its lack of phase relationship with the sunspot number curve (Hatton, 1980), etc.

In order to investigate the nature of 11-yr cosmic-ray variation many authors use solar activity and obtain large sizes of modulating region. So in the 21st solar cycle if we use the solar activity (sunspot number or solar flares $\geq$ 1N), in order to estimate the size of the modulation region around the Sun, we have found that it is near the unambiguous value of 180 AU in a first order approximation. But according to the equation of transfer the agent modulating cosmic-rays is proportional to the solar-wind speed or any other related index (Chirkov, 1985) then the conclusions on large sizes of cosmic-ray modulation region will be incorrect. So using the time-lag of solar flares of imp $\geq$ 1B or the high-speed solar-wind streams with respect to the cosmic-ray intensity, we estimate the sizes of cosmic-ray modulating region 40 AU. This result continues to confirm the fact that the dimensions of the heliosphere are not constant during a given solar cycle but depend upon the level of activity. That is the heliosphere has a larger size during the more active cycles.

On the other hand, looking at the time-lags of previous cycles we see that the hysteresis effect of cosmic-ray intensity behind solar activity as measured by the sunspot number exhibits a different behaviour during even and odd solar cycles (Table II). The phase-lag of cosmic-ray intensity is greater in even than in the odd cycles. This is due to the 22-yr variation in the time-lag, already found by Nagashima and Morishita (1980b) and Otaola *et al.* (1985). Indeed particles reach the Earth more easily when their access route is by the heliospheric polar regions than when they gain access along the current sheet (Kota and Jokipii, 1982). In this case as the route of access becomes longer due to the wanness of the neutral sheet the time lag r is also longer as one would expect from theoretical considerations. This model can not explain, however, the two maxima structure of the even cycles.

At last the observed periodicity of the yearly correlation coefficient of cosmic-ray intensity with every one of the parameters (sunspot number, flares $\geq$ 1B, streams, flare-generated streams, corotating streams) is very characteristic. In every two years, (even years), we have greater values of the correlation coefficient than in the other years. In the case of the correlation coefficient between the cosmic ray intensity and A_P index we cannot see the same behaviour. A similar tendency of the yearly correlation coefficient appeared also in the previous cycle (20 cycle) (Mavromichalaki and Petropoulos, 1984), but was not reinforced because there was confusion with the reversal of solar magnetic field.

TABLE II

The time lag of cosmic-ray intensity behind solar activity for different solar cycles.

Solar cycle	17	18	19	20	21
Time-lag (months)	9	1	10–11	2	16

Sugiura and Poros (1977) have shown the existence of highly correlated quasi-biennial variations in the geomagnetic field and in the solar activity expressed by the sunspot number or by the Ottawa 10.7 cm solar flux. The nature of the highly-correlated solar and geomagnetic oscillations is not yet understood, but there is the possibility that the 2-yr variation in the cosmic-ray intensity is connected to the 2-yr variation in solar activity via geomagnetic effect.

Attolini *et al.* (1986) have shown also that there is significant evidence of biennial variation in the cosmic-ray intensity. The origin of this intensity change has to be found in a geomagnetic effect, correlated to the solar activity.

Conclusions

From the analysis of cosmic-ray intensity data and the other solar-interplanetary and geophysical parameters using the hysteresis effect we can draw the following conclusions:

(1) The cosmic-ray modulation during the 21st solar cycle is more closely linked to the solar flares ≥ 1B than to the current sunspot number. This result makes questionable the reliability of the evaluation of the secular behaviour of solar activity done according to the observed abundance of the Carbon-14 or any other radioactive atom. It explains only the irregular shape of the cosmic-ray modulation, its lack of phase relationship with the sunspot number curve, the lack of secondary maximum etc.

(2) Some characteristic solar cycle phenomena observed in the cosmic-ray intensity during the 21st solar cycle such as the secondary maximum, the large time-lag of cosmic-ray intensity behind solar activity, etc., comparing with the corresponding ones of the previous solar cycle (20 cycle) establish clearly a marked distinction between even and odd solar activity cycles which in turn are reflected in cosmic-ray intensity, high-speed streams and geomagnetic activity.

(3) All these solar cycle phenomena except of the secondary maximum can be explained in terms of different processes influencing cosmic-ray transport in the heliosphere. During even cycles convection play the most important role while during odd cycles diffusion dominates. The effect of drift only determines how the particles gain access to the observation points: the charge-dependent effects are not the dominant processes in cosmic-ray modulation.

The existence of two maxima in the cosmic-ray intensity and the other indices can be explained by the superposition of the two components of the coronal magnetic field. One due to the poloidal field which exists on the solar surface and one due to the convection of the toroidal field into poloidal or radial fields.

(4) Significant evidence exists of the biennial variation in the cosmic-ray intensity, which appeared in the correlation coefficient of the cosmic-ray intensity with the sunspot number, the solar flares and the streams.

Acknowledgement

Thanks are due to the experimental groups which provided all these data and to the Director of WDC-A for Solar Terrestrial Physics. Thanks are also due to Mrs. P. Tatsi for her technical help.

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