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ΠΡΟΕΔΡΙΑ ΓΕΩΡΓΙΟΥ ΜΕΡΙΚΑ

ΑΣΤΡΟΝΟΜΙΑ.— **Periodic variations of the Cosmic-Ray diffusion coefficient related to high-speed solar-wind streams,** *by J. Xanthakis, H. Mavromichalaki, B. Petropoulos, E. Marmatsouri, A. Vassilaki**, διὰ τοῦ Ἀκαδημαϊκοῦ κ. Ἰωάννη Ξανθάκη.

ABSTRACT

A three dimensional model for the calculation of cosmic-ray intensity of Inuvik station during the 20th and 21st solar cycles is given. Especially we have studied the coefficient K of the used parameter of sunspot number in terms of high-speed solar-wind streams and have tried enough successfully to relate this coefficient with the diffusion process of cosmic rays in the interplanetary space.

Analyzing these two data sets for the time period 1964-1985 into a network of trigonometric series we have observed similar periods in the two sets. It means that we have the same in general lines variations in the high-speed streams as well as to the coefficient K expressed by this way the diffusion coefficient of cosmic-rays.

1. INTRODUCTION

The temporal variation in the cosmic-ray flux which is induced by changing conditions in the heliosphere is what we refer as the solar cycle modulation of the cosmic rays. More than thirty years ago Forbush (1958) pointed out that there is an inverse correlation between cosmic-ray intensity

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and relative sunspot number expressed by the Zûrich number R with a cyclic period of 11-years.

The relations between the solar-activity parameters and the cosmic-ray intensity have been studied by different authors (Xanthakis, 1971; Pomerantz et al, 1974; Nagashima and Morishita, 1980 etc). Balasubrahmanyan (1969) has found a relation between the cosmic-ray intensity and the geomagnetic activity. In all cases bysteresis effect between the different parameters and cosmic-ray intensity is clearly manifested in the dependence of cosmic-ray intensity on the magnitude of the above parameters (Mavromichalaki and Petropoulos, 1984). Some researchers explain the hysteresis effect by the large dimensions of the cosmic-ray modulation region (100-200 AU) (Simpson, 1963; Dorman, 1967).

Some years before Xanthakis, Mavromichalaki and Petropoulos (1981) in order to study the cosmic-ray modulation in the 20th solar cycle gave an elaborated model. According to this the modulated cosmic-ray intensity that was measured by the ground based stations is equal to the galactic cosmic -ray intensity (unmodulated) at a finite distance-corrected by a few appropriate solar and terrestrial activity indices which causes the disturbances in interplanetary space. Using the sunspot number R, the geomagnetic index A_p and the number of proton events N_p the corresponding cosmic-ray intensities have been calculated by proper values of the constant C and coefficient K (see below equs. (1), (2). The constant C has a constant value for each station which is rigidity dependent and the coefficient K is related to the diffusion coefficient of cosmic-rays and its transition in space.

In this work we have extended this model into the 21^{st} solar cycle and have studied especially the coefficient K which is mainly responsible for the 11-year modulation of cosmic-rays. This coefficient can be well related to the diffusion process of cosmic-rays according to the «diffusion-convection» model of cosmic-rays and its transition in interplanetary space, as it is in inverse relation with the size of the polar coronal holes. So a further study of this coefficient in relation with the high-speed solar-wind streams taken by the catalogue of Lindblad and Lundstedt (1981) and Mavromichalaki, Vassilaki and Marmatsouri (1988b) gave many interested results.

2. SELECTION OF DATA

In order to study the long-term modulation of cosmic-ray intensity in solar cycles 20^{th} and 21^{st} we have used the monthly values of cosmic-ray intensity by the Neutron-Monitor station of Inuvik (Super NM-64), Cut-off Rigidity 0.18 GV) over the time period 1964-1985. These data corrected for pressure are normalized for each solar cycle by the expression

$$\frac{I_i - I_{min}}{I_{max} - I_{min}}$$

where I_{min} and I_{max} are respectively the minimum and maximum intensity of cosmic rays during each solar cycle and I_i is the corresponding monthly value of cosmic-ray intensity. With this method the intensities at solar minimun are taken equal to 1.00 and at solar maximum are taken equal to zero.

The monthly values of solar flares of importance $\geq$1B, N_F, the monthly values of relative sunspot number R (Zurich Observatory) and the monthly values of geomagnetic index A_p have been taken from Solar Geophysical Data Reports. The monthly values of solar — wind streams of high— speed have been obtained by the catalogue of Lindblad and Lundstedt (1981) for the 20^{th} Solar cycle and the catalogue of Mavromichalaki et al. (1988b) for the 21^{st} solar cycle. We have defined high-speed solar-wind stream as the stream in which the difference between a smallest 3^{hr} velocity value for a given day and the largest 3-hr value for the following day is greater than or equal to 100 km. sec^{-1}.

Moreover we have taken into account in our analysis the time-lag of cosmic-ray intensity with respect the different parameters we have used. These phases have been taken by the papers of Mavromichalaki and Petropoulos (1984) for the 20th solar cycle and Mavromichalaki et al. (1988a) for the 21^{st} solar cycle.

From all these detailed data we can calculated the values of the coefficient K according to the expression:

$$I = C - 10^{-3}\,(KR_{(t-2)} + 4N_{F\,(t-4)} + 12A_{p(t)}) \qquad (1)$$

for the 20th solar cycle, and

$$I = C - 10^{-3} \left(KR_{(t-17)} + 6N_{F\,(t-6)} - 16A_{P\,(t+16)} \right) \qquad (2)$$

for the 21^{st} solar cycle,

where C is a constant which depends linearly on the cut-off rigidity of each station (C=0.94 for the Inuvik station), and K is the coefficient which is probably related to the diffusion coefficient of cosmic-rays. The most important solar and terrestrial indices - R, N_F and A_P - which are affected cosmic-ray modulation are taken with their time lags (Mavromichalaki, et al. 1988a).

The values of K which are calculated from the relations (1) and (2) have been analysed into trigonometric series which are given in the Table I for the 20th and 21st solar cycles. This analysis is appeared also in the Figure 1. It is remarkable to note that periodic variations of 132,24 and 12 months are appeared in the two solar cycles. Moreover in the 21st solar cycle periodic variations of short-term duration are appeared, which are 12, 8, 6,4,3 and 2 months. In the beginning of the 21st solar cycle (1977-78). It is appeared an enhancement of the K values which perhaps due to the large time lag between the cosmic-ray intensity and the sunspot number during the last solar cycle. The short term periods of the 21st solar cycle in the coefficient K data are confirmed by a spectrum analysis according to Blackman and Turkey method (Mitchell, 1966) this analysis revealed the existence of periodicities of 6 and 3 months with a significance level higher than 90% (Fig. 2).

The calculated by the relations of the Table I values of the coefficient K (K_{cal}) and the calculated ones by the relations (1) and (2) are given in Fig. 3. The standard deviation is $\sigma = \pm 0.7$ for the 20th solar cycle and $\sigma = \pm 1.22$ for the 21^{st} solar cycle.

3. SOLAR - WIND STREAMS

As it is known the high-speed solar wind streams (HSWS) emitted by the coronal holes or associated with strong active regions emitting solar flares are the main cause of galactic cosmic-ray intensity variations. Iucci et al. (1979) have shown that when the Earth centers the region of high-speed solar- wind stream the cosmic ray intensity decreases. This decrease is proportional to the differences between the plasma velocity during the HSWS and the quiet solar wind. Dorman et al. (1985) have found that the intensity of

TABLE I.

Analytical expression of the coefficient K for the two solar cycles.

20th Solar Cycle

$$K = -3{,}5 \cos\frac{2\pi}{132}(t - 1964\ I) + a_n \sin\frac{2\pi}{24}t + b_n \sin\frac{2\pi}{12}t$$

a_n	t	b_n	t
−5,0	1965V-1966I	5,0	1973I-73III
−2,0	1967XII-65XII	−2,5	1973IV-74II
+4,0	1070IV-71VII	−6,0	1974XI-75XII

21th Solar Cycle

$$K=7{,}98\pm0{,}78-6 \sin\frac{2\pi}{132}(t-1979V)+10 \sin\frac{2\pi}{24}(t-1974VII)+P$$

$$P=a_1 \sin\frac{2\pi}{12}t + a_2 \sin\frac{2\pi}{8}t + a_3 \sin\frac{2\pi}{6}t + a_4 \sin\frac{2\pi}{4}t + a_5 \sin\frac{2\pi}{3}t + a_6 \sin\frac{2\pi}{2}t$$

a_1	t	a_2	t
+8	1976II-76VII	+15	1977IV-79VII
+2,0	1977VII-78I	+18	1978III-78VII
−8	1978X-79IV	−5	1979VI-79X
−4	1979XII-80XI	−6	1978VI-78X

a_3	t
+ 6	1975XI-76II, 1976VIII-77II, 1984V-84IX
− 3	1980VI-80XII
+ 3	1981IX-82I, 1982V-82VIII, 1976X-77I
- 4	1984IV-84VII
- 11	1977VIII-77XI
+12	1977-78III

TABLE I (continued)

a_4	t
— 5	1974XII-78IV, 1978
+ 2	1975I-75V
— 2	1975II-75VII
— 4	1975VIII-75XII, 1979IX-80I, 1981IV-80VIII
— 3	1976I-76VII, 1983V-83IX, 1983VII-83XI
+175	1977XI-78I
+67	1978III-78V
— 6	1982VIII-83I
+ 3	1982X-83II

a_5	t
+5	1977V-77VII
—4	1982X-82XII

a_6	t
—10	1978VI-78IX
+7	1978XI-79II

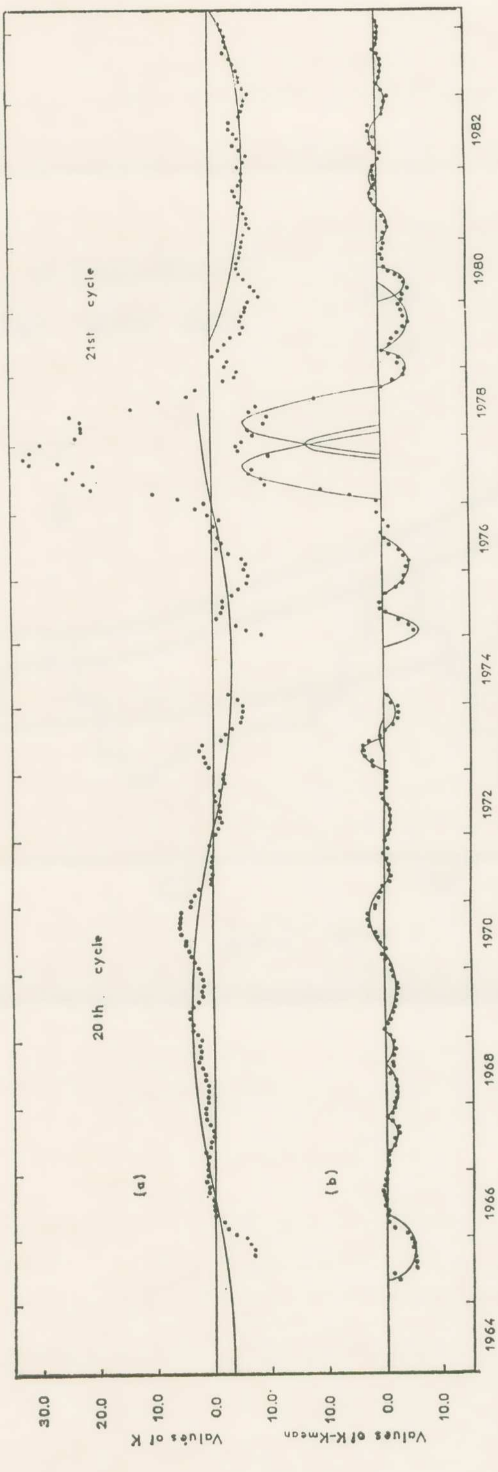

Fig. 1. Variation of the coefficient K as a function of time and its periodicities from 1964 to 1984. The continuous line gives the calculated values and the points give the observed values of K.

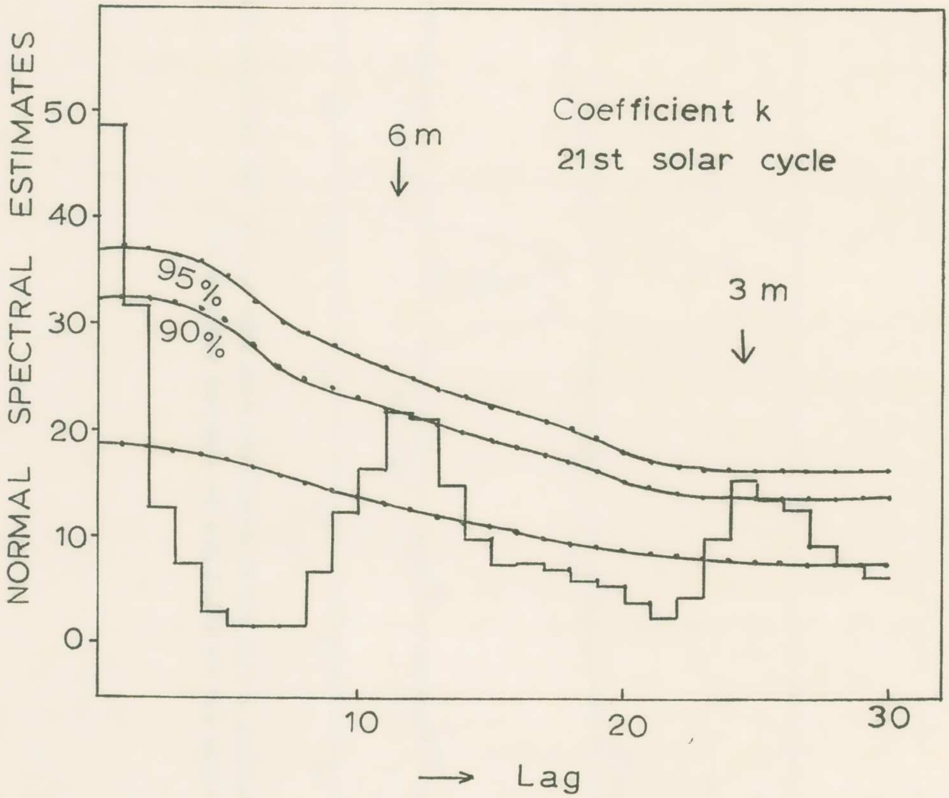

Fig. 2. Power spectrum analysis of coefficient K data for the 21st solar cycle.

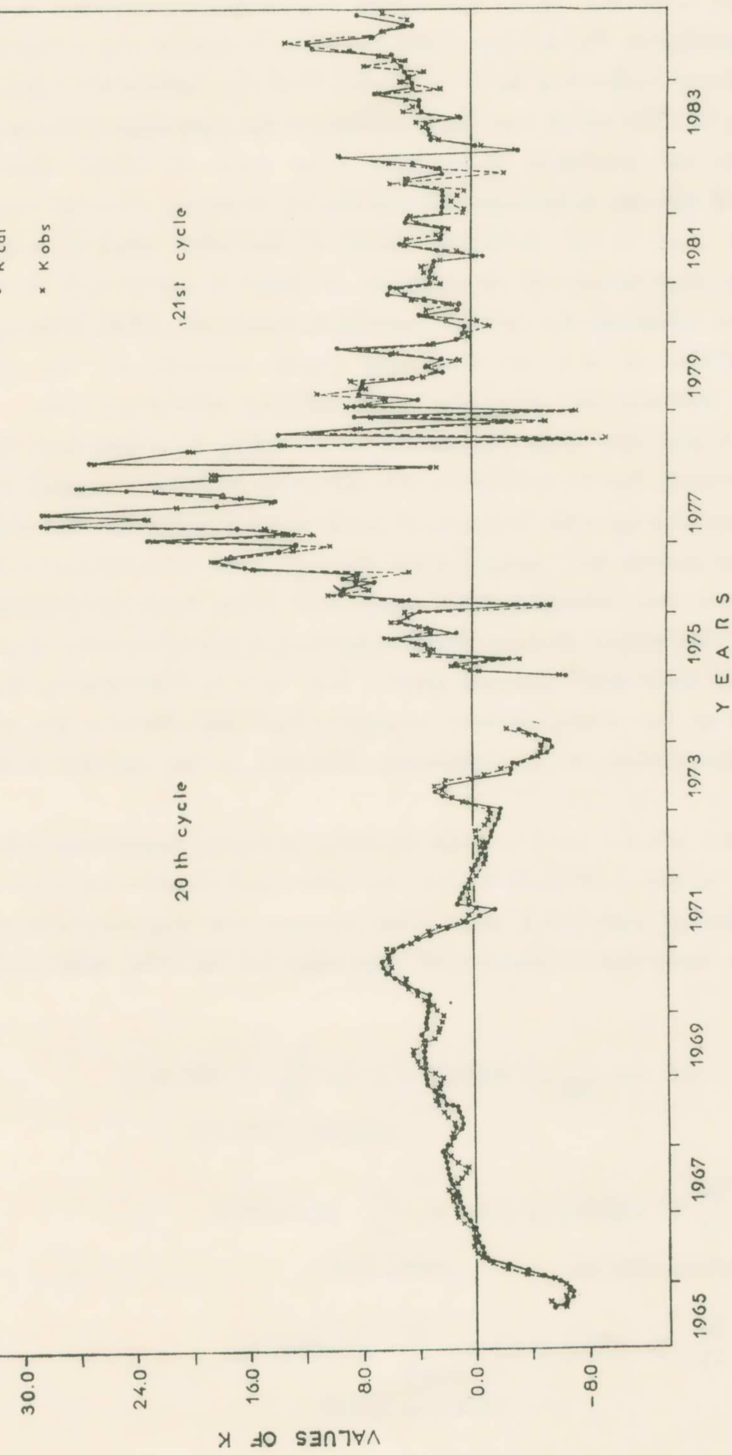

Fig. 3. Observed values of K given by the relation (1) and (2) for the two solar cycles and calculated values of this coefficient (Kcal) given by the relations of the Table I.

cosmic-ray decreases inside the stream anisotropically. Kuzmin et al. (1985) have investigated the nature of the variation in cosmic ray anisotropy with solar activity cycles and have concluded that the cosmic-ray intensity level was lower in 1976 which was the minimum of the past solar cycle than in 1965 which was the minimum of the past solar cycle. It means that the fast solar wind streams determine the cosmic-ray intensity at solar minima. On the other hand in the declining phase of the solar cycle 20 a number of anomalus phenomena of modulation of galactic cosmic-ray by the solar wind were observed for several years (Charakhchyan, 1986; Mavromichalaki et al., 1988a) as it is an unusually rapid recovery of the cosmic-ray intensity immediately after the solar activity maximum e.t.c.

In a previous work (Xanthakis et al., 1981) we found that the coefficient K which can be related to the diffusion process of cosmic rays is in inverse correlation with the size of polar coronal holes for the years 1965-1976. It is known that coronal holes are associated with magnetic field lines which open into interplanetary space and have been indentified as the source of the major streams of fast solar wind in interplanetary space. So the high-speed solar wind streams play a key role in determining the spatial structure of the interplanetary magnetic field and become the «channels» for the penetration of the cosmic-ray intensity in the vinicity of the heliosphere.

In the present work in order to study this good connection between the variation of the coefficient K and the solar-wind streams we have analysed the number of high-speed solar wind streams into trigonometric series.

The analytical expression of this serie for the 20th solar cycle is the following.

$$S^{cal} = 2,7 - 0,6 \sin \frac{2\pi}{192} (T\text{-}1963I) - \underset{1963IX-1965III}{1,5 \sin \frac{2\pi}{36} (T\text{-}1963IX)}$$

$$- \underset{1965VIII\text{-}68VIII}{1,5 \sin \frac{2\pi}{36} (T\text{-}1965VIII)} + \underset{1969I\text{-}70X}{1,0 \sin \frac{2\pi}{36} (T\text{-}1969V)} \qquad (3)$$

$$+ 1,2 \sin \frac{2\pi}{12} (T\text{-}1973I) + \underset{1974VII\text{-}76VII}{1,5 \sin \frac{2\pi}{24} (T\text{-}1974VII)}$$

$$+ a\sin\frac{2\pi}{6}T + b\sin\frac{2\pi}{3}T$$

We observed also variations of short periods given by the expression

$$P = a\sin\frac{2\pi}{6}T + b\sin\frac{2\pi}{3}T$$

The values of coefficients a and b are given in the Table II The corresponding expression for the 21^{st} solar cycle is

$$S^{cal} = 3{,}0 + a_1 \sin\frac{2\pi}{24}T \times a_2\frac{2\pi}{8}T + a_3\sin\frac{2\pi}{6}T + a_4\sin\frac{2\pi}{4}T + a_5\sin\frac{2\pi}{3}T \qquad (4)$$

The coefficients a_1, a_2, a_3, a_4, and a_5 are given in the Table III.

We ought to note that we observe periods of 132, 36, 24, 12, 8, 6, 4 and 3 months during the two solar cycles. A graphic presentation of this analysis is appeared in Figs 4 and 5. The standard deviation between observed and calculated values are 0.3. A synoptic picture of all found periods in the coefficient K and the solar wind streams data are given in Table IV.

DISCUSSION AND CONCLUSIONS

As it is known the transport of cosmic rays in the interplanetary magnetic field is the consequence of four basic effects diffusion, convection, cooling and gradient and curvature drifts. The resulting transport equation for the distribution function may be written

$$\frac{df}{dt} = \nabla(K \cdot \nabla f) - V.\ \nabla f + \frac{1}{3}\nabla V\frac{df}{dlnP} \qquad (5)$$

where P is the momentum, V is the solar wind velocity and K is the diffusion tensor (Jokipii and Kota, 1985).

A variety of solutions of this equation has appeared in the literature. A straightforward application of this equation leads to a situation in which the particle drifts play a very important and perhaps dominant role in the modulation of galactic cosmic-rays (Kota and Jokipii, 1982).

TABLE II.

The coefficients a and b of the expression P for the short-term periods of the total high-speed streams (20th solar cycle).

$$P = a \sin \frac{2\pi}{6} t + b \sin \frac{2\pi}{3} t$$

a	t
—1,0	1964II-64V, 1964IV-64VII, 1965II-65VI, 1966IV-67IV, 1967II-67V, 1971X-72IV, 1973VII-74II, 1973VIII-73XI, 1974VII-74X, 1974X-75I, 1976XI-77II, 1977IV-78I
+1,0	1964VIII-65XI, 1965XI-66II, 1967III-67VI, 1970XII-1971XII, 1971III-71XII, 1972X-73I, 1976VII-76X
—1,5	1967XI-68V
—2,0	1975V-75VII, 1976IX-76XII
+2,0	1966I-66IV, 1969I-69XI, 1972IV-72X, 1976IX-76XII
+2,5	1974XII-75VI, 1975X-76II
—2,5	1975I-75VII, 1975IX-75XII
+3,0	1977I-77IV

b	t
—1,0	1968VI-68IX, 1968XI-69III
+1,0	1969V-69VIII, 1972XII-73IV, 1978II-78V
—1,5	1969X-69XII, 1971I-71IV
—2,0	1968X-69I
—2,5	1964IX-69XII
—3,5	1977II-77V
+3,0	1968I-68V, 1970VI-71IX
+2,0	1970VI-70X

TABLE III.

Values of coeficients a, a_2, a_3, a_4 and a_5 of the stream analytical expression for the 21st solar cycle.

a_1	t	a_2	t
—1,2	1976III-77III	- 1,0	1980III-80VII
—2,0	1977I-78II	- 2,0	1984VI-84X

a_3	t
—1,0	1975VIII-75XI
+1,6	1976IV-76VII, 1977III-7VI, 1977VI-77IX, 1977III-77V, 1978XI-79II, 1979IX-79XII, 1981IX-81XII
+2,0	1977VIII-77XI, 1979II-79V, 1982VI-82IX, 1982VIII-82XI

a_4	t
—2,0	1978VIII-78XII, 1979II-79XI, 1980XI-81I
+120	1981VI-81X, 1978I-76VII
—1,0	1976VIII-76VII, 1980VII-80XI

a_5	t
+1,0	1978III-78VI, 1978V-78III, 1979XII-80III, 1980XII-81III 1982IV-82VII
—1,0	1981XII-82III, 1983I-83IV
—2,0	1984I-84IV, 1984X-86I

Table IV. Synoptic table of the appeared periods in the coefficient K and solar wind streams.

T (20th Solar cycle)

Coefficient K	132		24	12		
H.S.W.S.	192	36	24	12	6	3

T (21st Solar cycle)

Coefficient K	132	24	12	8	6	4	3
H.S.W.S.		24		8	6	4	3

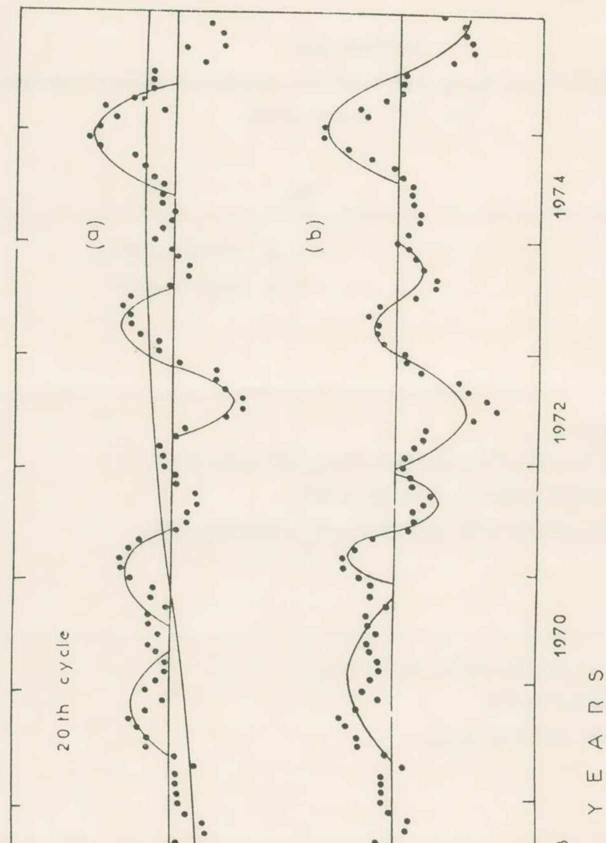

Fig. 4. Periodic variations of the number of the high-speed solar-wind streams during the 20th solar cycle. The continuous line gives the calculated values and the points give the observed values of S.

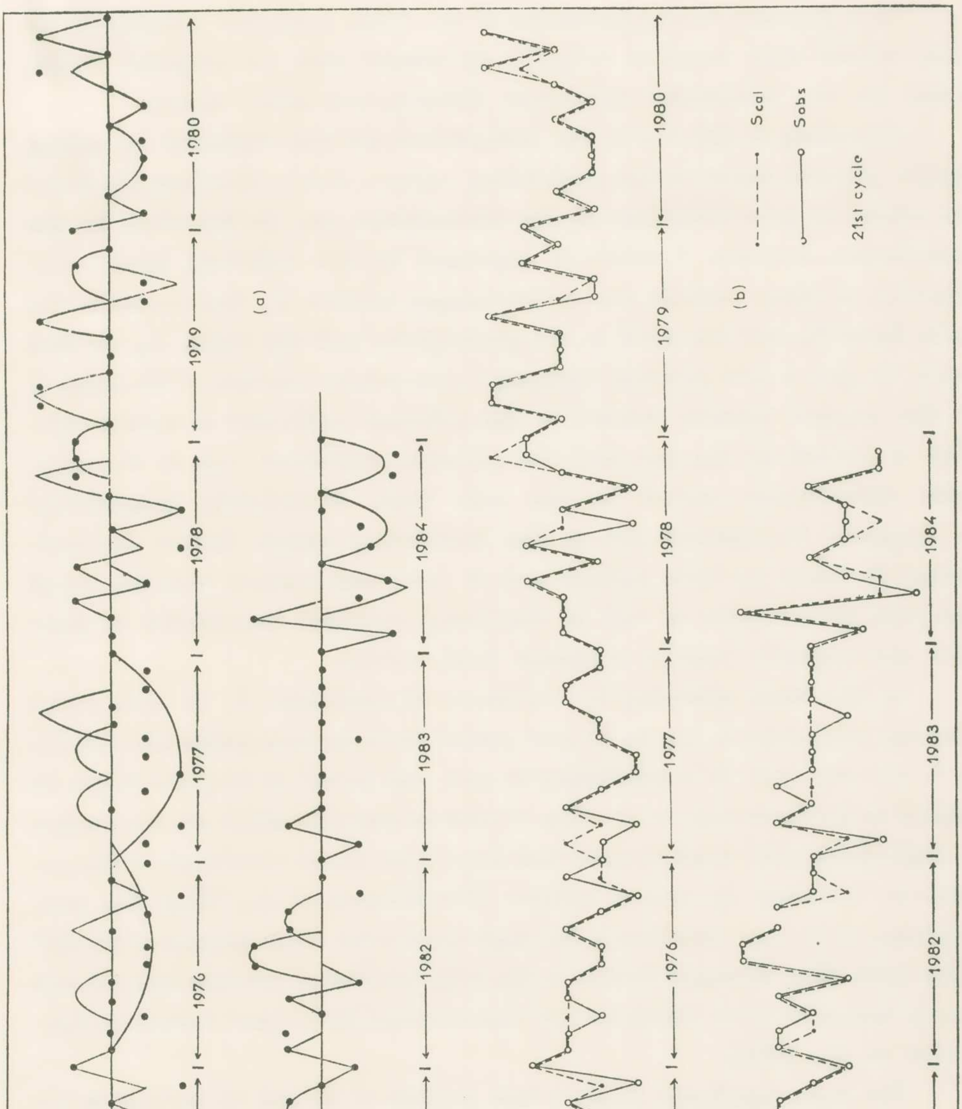

Fig. 5. Periodic variations of the high-speed solar-wind streams during the 21st solar cycle.

In a previous work (Xanthakis et al., 1981) a detailed analysis of the observations were found in complete agreement with our proposed model, based on the spherically symmetric diffusion-convection theory.

According to this theory the modulations are well explained by setting proper physical states in the modulating region, if it is clear how the states are related to solar activities. So the modulations can be described by the distribution function f which is expressed by the following linear combination of three indices: one is the sunspot number R, the second is the solar flares N_F and the third is the geomagnetic activity index A_p. In that work we give a new physical meaning to the source function of the index R of the sunspot number related to the diffusion coefficient of cosmic rays. This is derived by the fact that the diffusion coefficient due to the magnetic disturbances carried on the solar wind is inversely proportional to magnetic fluctuations ΔH in the modulating region. Indeed the coefficient K which we have defined here is in inverse relation with the size of the polar coronal holes as well as the yearly averaged magnitudes of positive and negative polarity magnetic field vectors.

In this work searching for variations of coefficient K we have found that the coefficient K has an 11-year period for both solar cycles (20 and 21) as it was expected. It is interesting to note this period of 11-years might be related to the flares and / or the area of polar coronal hole which are the sources of high-speed solar wind streams and have been found correlated to the cosmic-ray intensity by several authors (Hundhausen et al., 1980). The non-existence of 11-year variation in the high-speed solar wind streams in the 21^{st} solar cycle (Fig. 4) might be due to the large number of coronal-hole streams during this solar cycle which are not characterized by 11-year variation (Xanthakis et al., 1988).

The more significant point is that periods of 24 and 12 months in the analysis of coefficient K data as well as in the analysis of solar-wind streams are observed.

These two periodicities are observed to be variable in amplitude and phase and not correlated with sunspot cyclic variations. (Attolini et al., 1987) noted a two year variation in cosmic ray intensity examining the Climax Neutron monitor data. This periodicity seems to depend on the magnetic polarity of the interplanetary medium.

The two year variation, as well as the annual periodicity have been also identified in neutron monitor data by Kolomeets et al., (1973), and stratospheric sounding data by Charakhchyan et al. (1979 a,b), Okhlopkov et al. (1979), and in the low-energy cosmic ray intensity in space (Charakhchyan, 1986) We note that the periodicity of two years has been also found in some solar phenomena as the number of sunspots R for the time period (1856-1955) (Shapiro, 1962; Sakurai, 1979), for the time period (1970-76) and also the neutrino flux (Sakurai, 1981) measured by Davis (1978). The two year periodicity and the annual periodicity had been predicted by Dorman and Putskin (1981).

They have proposed that the possible natural large-scale pulsations of the solar cavity are the origin of a new type of cosmic-ray variations with characteristic periods varying from 1-2 years to tens of years.

For both solar cycles short periodicities of 6 and 3 months have been found in coefficient K and in high-speed solar wind streams. Moreover periodicities of 8 and 4 months have been reported during the 21^{st} solar cycle. Such variations have been investigated on the basis of cosmic-ray measurements on sounding balloons by Okhlopkov et al. (1986). They have observed significant peaks with periods $T=2$, 1.5, 1, 0.75 and 0.50 years in the frequency spectra.

The different behaviour of the coefficient K and the high-speed solar-wind streams during the two solar cycles for example the short term periodicities the sudden commencement of K during the beginning of the 21^{st} solar cycle are due to the distrinction which there is between even and odd solar cycles. This is explained in term 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 determine how the particles gain access to the observation points. That is charge dependent effects are not the dominant processes in cosmic-ray modulation (Otaola et al., 1985; Mavromichalaki et al., 1988a).

From the above analysis it is resulting that the diffusion coefficient of cosmic-rays as has been defined by the diffusion-convection theory is mainly responsible for the modulation and the propagation of cosmic rays through the solar system to the Earth's orbit.

In the future a detailed study of the diffusion coefficient of cosmic rays and the magnetic disturbances carried on the solar wind during more than two solar cycles will lead us to a better understanding of the relations among the coronal structure, the interplanetary structure and the cosmic ray propagation in solar system.

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ΠΕΡΙΛΗΨΗ

Περιοδικὲς μεταβολὲς τοῦ συντελεστοῦ διάχυσης τῶν κοσμικῶν ἀκτίνων σὲ σχέση μὲ τὰ ταχέα ρεύματα τοῦ ἡλιακοῦ ἀνέμου

Σ' αὐτὴ τὴν ἐργασία ἕνα τριδιάστατο πρότυπο δίνεται γιὰ τὸν ὑπολογισμὸ τῆς ἔντασης τῆς Κοσμικῆς Ἀκτινοβολίας γιὰ τὸν 20ο καὶ 21ο ἡλιακὸ κύκλο. Εἰδικώτερα ἔχει γίνει μιὰ προσπάθεια νὰ συσχετισθῆ ὁ συντελεστὴς K τῆς παραμέτρου τῶν ἡλιακῶν κηλίδων μὲ τὰ γρήγορα ρεύματα τοῦ ἡλιακοῦ ἀνέμου καὶ ὡς ἐκ τούτου μὲ τὶς διαδικασίες διάχυσης τῶν Κοσμικῶν ἀκτίνων στὸ μεσοπλανητικὸ χῶρο.

Ἀναλύοντας αὐτὲς τὶς σειρές, τῶν δεδομένων γιὰ τὴν χρονικὴ περίοδο 1964-1985 σὲ τριγωνομετρικὲς σειρὲς παρατηρήσαμε ὅμοιες περιόδους στὶς δυὸ σειρές. Αὐτὸ σημαίνει ὅτι ἔχουμε σὲ γενικὲς γραμμὲς ὅμοιες μεταβολὲς τόσο στὰ ρεύματα τοῦ ἡλιακοῦ ἀνέμου ὅσο καὶ στὸ συντελεστὴ K ποὺ ἐκφράζει τὸ συντελεστὴ διάχυσης τῶν Κοσμικῶν ἀκτίνων.