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A PERIODICAL ANALYSIS OF THE COSMIC-RAY DIFFUSION COEFFICIENT AND THE HIGH-SPEED SOLAR-WIND STREAMS

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Abstract. A three-dimensional model for the calculation of cosmic-ray intensity of the 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 period in the two sets. It means that we have the same in general line 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 to 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 and relative sunspot number expressed by the Zürich 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 hysteresis 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 and Dorman, 1967).

Some years before Xanthakis *et al.* (1981), in order to study the cosmic-ray modulation in the 20th solar cycle, presented a more elaborate 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 cause 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

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calculated by proper values of the constant C and coefficient K (see Equations (1) and (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 21st 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 *et al.* (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 and 21, 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 minimum 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 (Zürich Observatory) and the monthly values of the 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 20th solar cycle and the catalogue of Mavromichalaki *et al.* (1988b) for the 21st 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 s^{-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 21st 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

$$I = C - [10^{-3} KR_{(t-17)} + 6N_{F(t-6)} - 16A_{P(t+16)}] \tag{2}$$

for the 21st 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 Table I for the 20th and 21st solar cycles. This analysis is also appeared in 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 (1977–1978) it is appeared to 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 confined by a spectrum analysis according to the Blackman and Turckey method (Mitchell, 1966). This analysis revealed the existence of periodicities of 6 and 3 months with a significance level higher than 90% (Figure 2).

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

TABLE I

Analytical expression of the coefficient K for the two solar cycles

20th solar cycle

$$K = -3.5 \cos \frac{2\pi}{132} (t - 1964\text{I}) + a_n \sin \frac{2\pi}{24} t + b_n \sin \frac{2\pi}{12} t$$

a_n	t	b_n	t
−5.0	1965V–1966I	5.0	1973I–73III
−2.0	1967XII–65XII	−2.5	1973IV–74II
+4.0	1970IV–71VII	−6.0	1974XI–75XII

21th solar cycle

$$K = 7.98 \pm 0.78 - 6 \sin \frac{2\pi}{132} (t - 1979\text{V}) + 10 \sin \frac{2\pi}{24} (t - 1974\text{VII}) + P$$

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

$$+ a_5 \sin \frac{2\pi}{3} t + a_6 \sin \frac{2\pi}{2} t$$

Table I (continued)

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

a_4	t
− 5	1974XII–78IV, 1978
+ 2	1975I–75V
− 2	1975II–75VII
− 4	1975VIII–75XII, 1979IX–801, 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

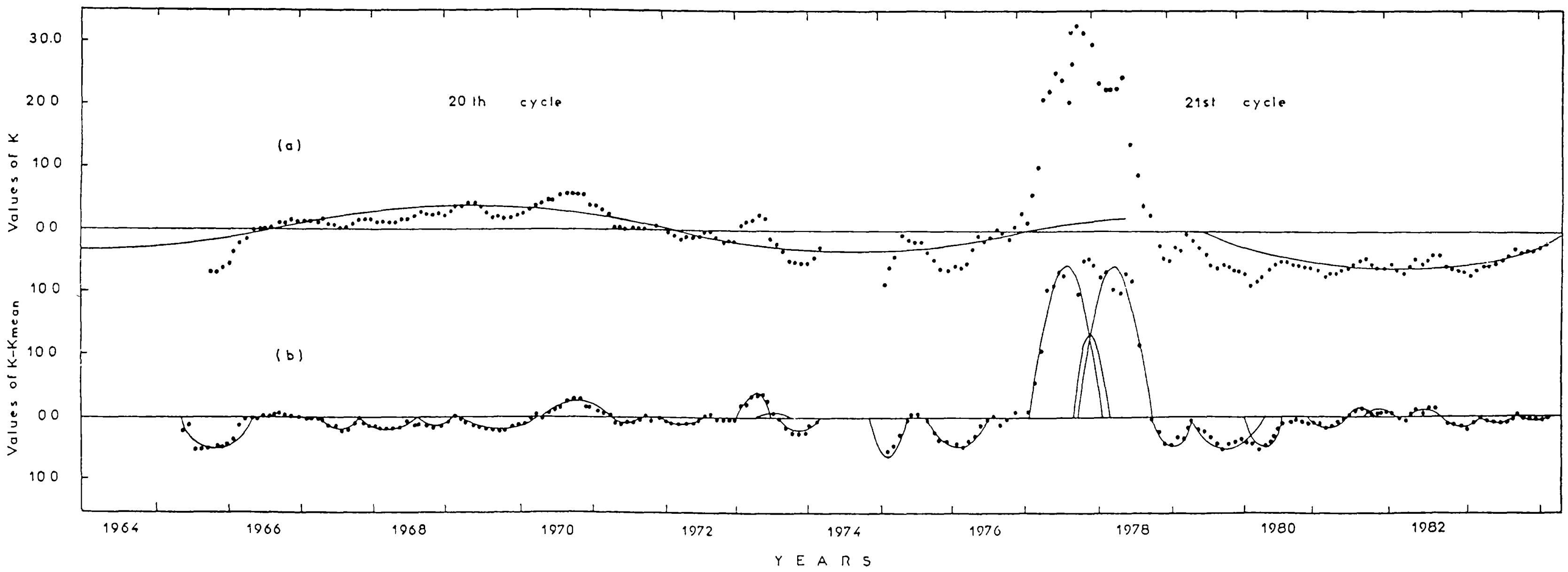

Fig. 1. Variation of the coefficient K as a function of time and its periodicities from 1964 to 1984. The continuous line gives the calculated values and the points give the observed values of K.

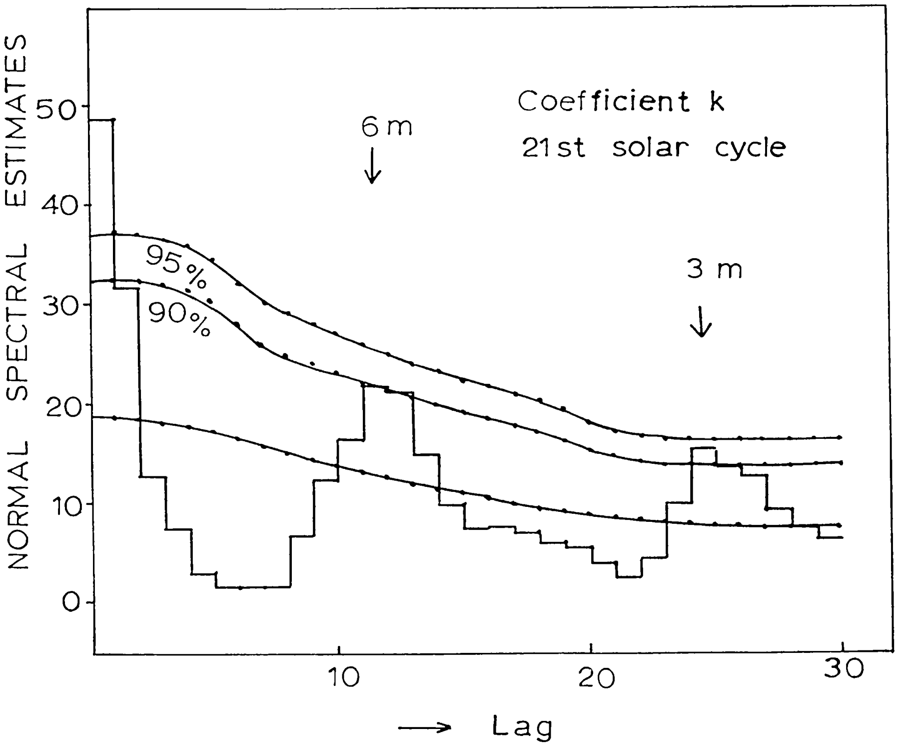

Fig. 2. Power spectrum analysis of coefficient *K* data for the 21st solar cycle.

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 enters 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) has found that the intensity of cosmic-ray decreases inside the stream anisotropically. Kuzmin *et al.* (1985) has 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 last 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 anomalous 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, etc.

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

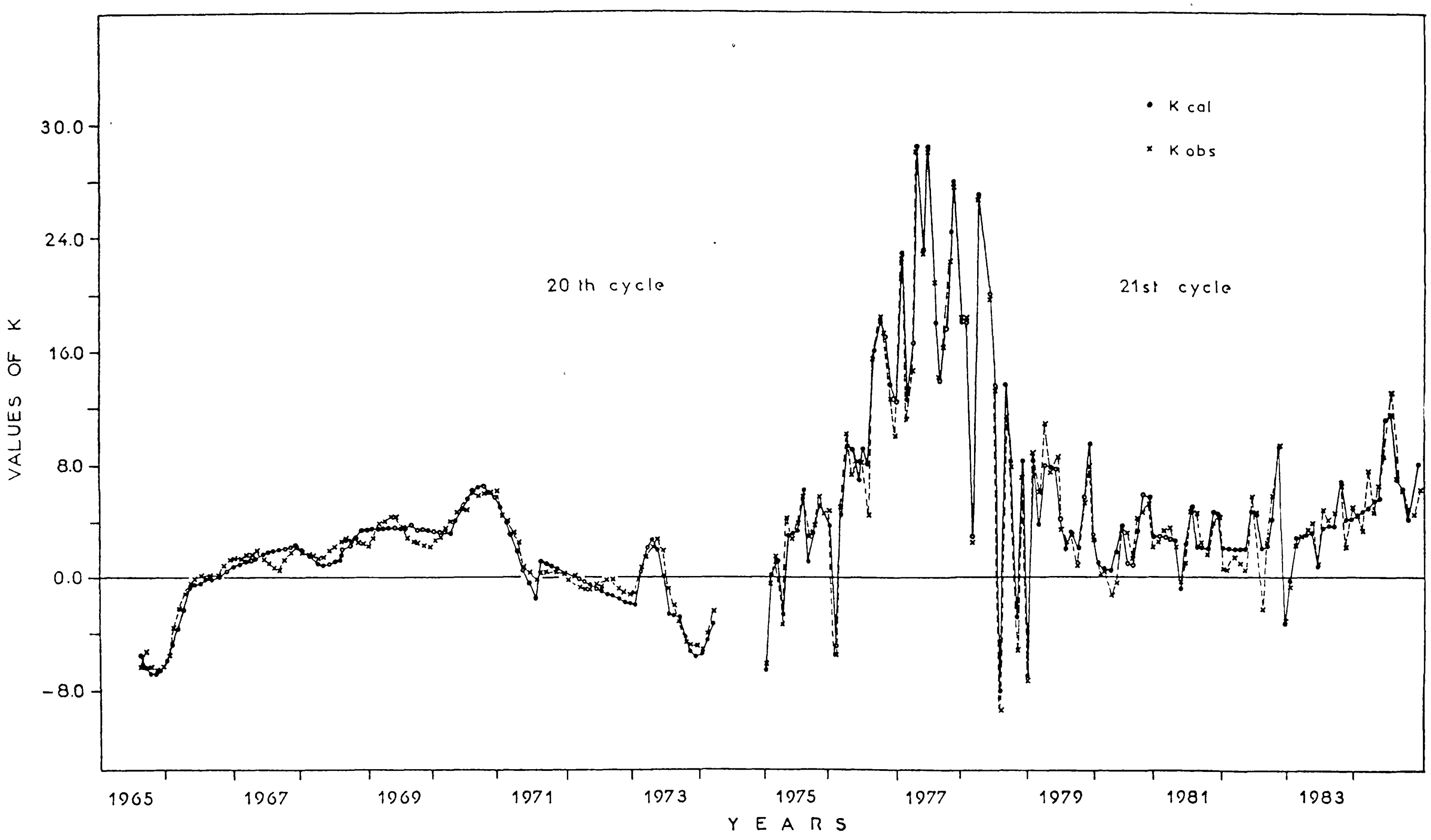

Fig. 3. Observed values of K given by the relations (1) and (2) for the two solar cycles and calculated values of this coefficient (K^{cal}) given by the relations of Table I.

identified as the source of the major streams of fast solar wind in interplanetary space. Thus 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

$$\begin{aligned} S^{\mathrm{cal}} = 2.7 &- 0.6 \sin\frac{2\pi}{192}(t - 1963\mathrm{I}) - \underset{1963\mathrm{IX}-1965\mathrm{III}}{1.5 \sin\frac{2\pi}{36}(t - 1963\mathrm{IX})} - \\ &- \underset{1965\mathrm{VIII}-68\mathrm{VIII}}{1.5 \sin\frac{2\pi}{36}(t - 1965\mathrm{VIII})} + \underset{1969\mathrm{I}-70\mathrm{X}}{1.0 \sin\frac{2\pi}{36}(t - 1969\mathrm{V})} + \\ &+ 1.2 \sin\frac{2\pi}{12}(t - 1973\mathrm{I}) + \underset{1974\mathrm{VII}-76\mathrm{VII}}{1.5 \sin\frac{2\pi}{24}(t - 1974\mathrm{VII})}\,. \end{aligned} \tag{3}$$

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	1969IX–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

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 Table II. The corresponding expression for the 21st solar cycle is

$$S^{\mathrm{cal}} = 3.0 + a_1 \sin \frac{2\pi}{24} t + a_2 \frac{2\pi}{8} t + a_3 \sin \frac{2\pi}{6} t +$$

$$+ a_4 \sin \frac{2\pi}{4} t + a_5 \sin \frac{2\pi}{3} t . \qquad (4)$$

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

We should 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 Figures 4 and 5. The standard deviation between observed and calculated values are ± 0.3.

TABLE III

Values of coefficients a_1, 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–77VI, 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
+ 1.0	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

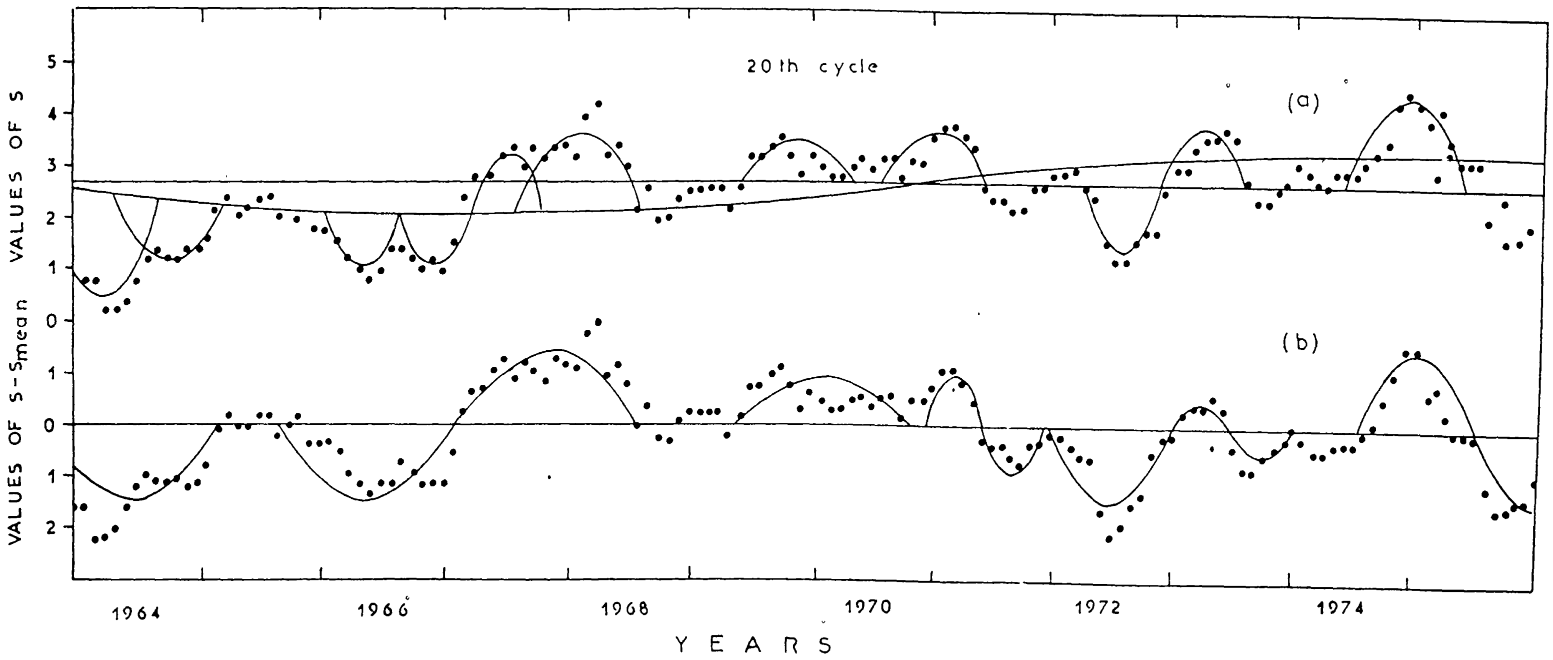

Fig. 4. Periodic variations of the number of the high-speed solar-wind streams during the 20th solar cycle. The continuous line gives the calculated values and the points give the observed values of S.

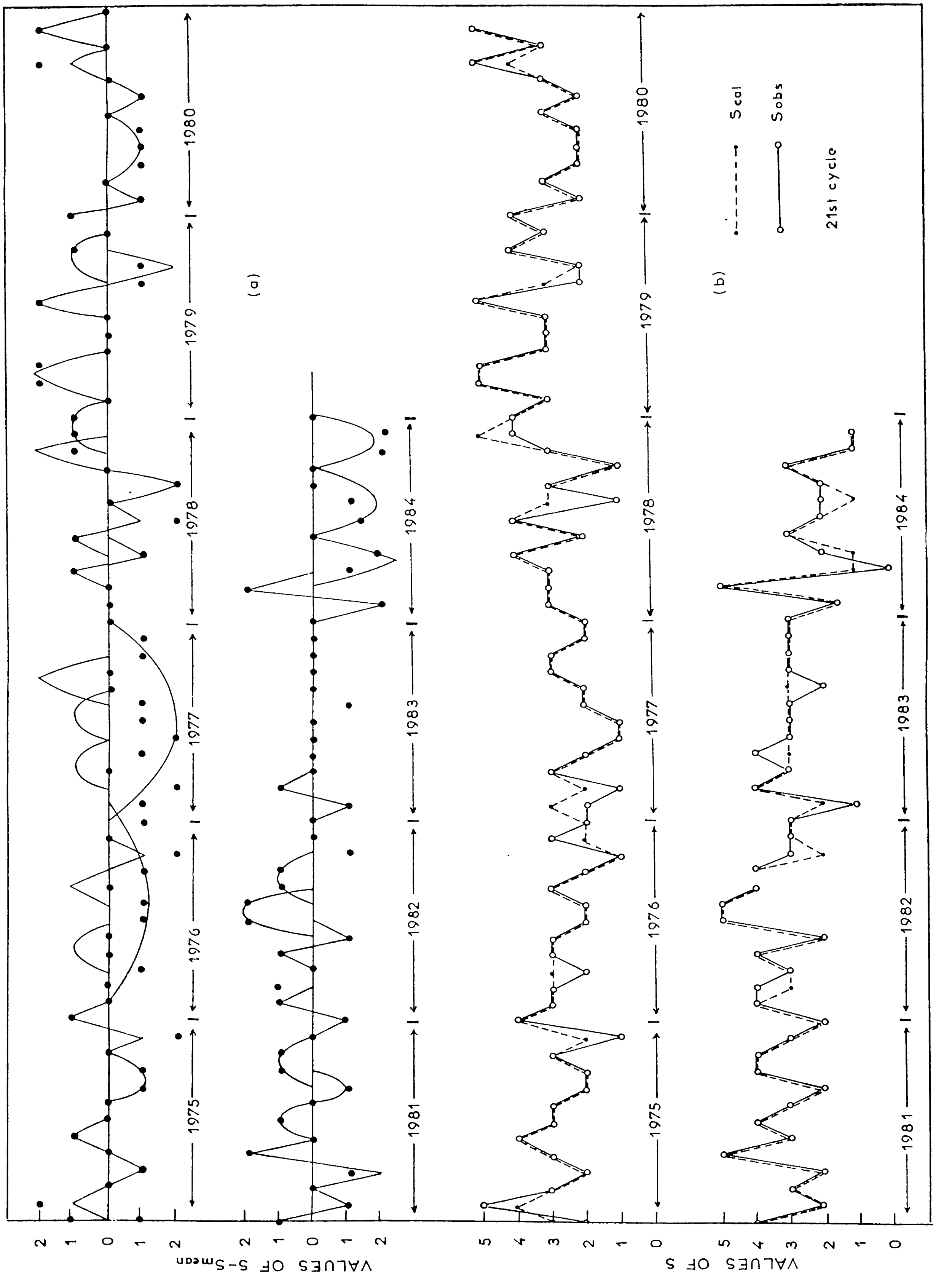

Fig. 5. Periodic variations of the high-speed solar-wind streams during the 21st solar cycle.

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

A synoptic picture of all found periods in the coefficient K and the solar-wind streams data are given in Table IV.

4. 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

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \nabla(K \cdot \nabla f) - V \cdot \nabla f + \frac{1}{3} \nabla V \frac{\mathrm{d}f}{\mathrm{d} \ln P} , \tag{5}$$

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).

In a previous work (Xanthakis *et al.*, 1981) a detailed analysis of the observations were found in complete agreement with our proposed model which 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 flare N_f, and the third is the geomagnetic activity index A_p. In that work we gave 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 $\overline{\Delta H}$ in the modulating region. Indeed, the coefficient K which we have defined here is in inverse relation 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 that this period of 11 years might be related to the flares and/or the area of polar coronal holes 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 21st solar cycle (Figure 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 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 also been identified in neutron monitor data by Kolomeets *et al.* (1973), and stratospheric sounding data by Charakhchyan *et al.* (1979a, 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 polar phenomena as the number of sunspots R for the time-period 1856–1955 (Shapiro, 1962; Sakurai, 1979) for the time-period 1970–1976 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 Ptuskin (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 21st 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 period $T = 2$, 1.5, 1.0, 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 21st solar cycle are due to the distinction 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 the solar system.

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References

Attolini, M. R., Cecchini, S., and Galli, M.: 1987, *Astrophys. Space Sci.* **134**, 103.

Balasubrahmanyan, V. K.: 1969, *Solar Phys.* **7**, 39.

Charakhchyan, T. N.: 1986, *Geomagnetizm i Aeronomiya* **26**, 8.

Charakhchyan, T. N., Okhlopkov, V. P., and Okhlopkova, L. S.: 1979a, *Proc. 16th Int. Cosmic Ray Conf., Kyoto* 3, 297.

Charakhchyan, T. N., Okhlopkov, V. P., and Okhlopkova, L. S.: 1979b, *Proc. 16th Int. Cosmic Ray Conf., Kyoto* 3, 308.

Davis, R., Jr., Evans, J. C., and Cleveland, B. I.: 1978, 'The Solar Neutrino Problem', in E. C. Flower (ed.), *Neutrino*, Purdue Univ. Lafayette, Vol. 78, p. 53.

Dorman, I. V. and Dorman, L. I.: 1967, *J. Geophys. Res.* **65**, 1593.

Dorman, L. I. and Ptuskin, V. S.: 1981, *Astrophys. Space Sci.* **79**, 397.

Dorman, L. I., Kaminer, N. S., Kuzmicheva, A. E., and Mumrina, N. Y.: 1985, *Proc. 19th Int. Cosmic Ray Conf., La Jolla* **5**, 293.

Dorman, L. I., Pimenov, I. A., and Churunova, L. E.: 1977, *Proc. 15th Int. Cosmic Ray Conf., Plovdiv* **3**, 268.

Forbush, S. E.: 1958, *J. Geophys. Res.* **63**, 651.

Hundhausen, A. J., Sime, D. G., Hansen, R. T., and Hansen, S. F.: 1980, *Science* **207**, 761.

Iucci, N., Parisi, M., Storini, M., and Villoresi, G.: 1979, *Nuvo Cimento* **26**, 429.

Jokipii, J. R. and Kota, J.: 1985, *Proc. 19th Int. Cosmic Ray Conf., La Jolla* **4**, 449.

Kolomeets, E. V., Mukhanov, I. V., and Shvartsman, Ya. E.: 1973, *Proc. 13th Int. Cosmic Ray Conf.* **3**, 1207.

Kota, J. and Jokipii, J. R.: 1982, *Astrophys. J.* **265**, 583.

Kuzmin, A. I., Samsonov, I. S., and Samsonova, Z. N.: 1985, *Proc. 19th Int. Cosmic Ray Conf., La Jolla* **5**, 250.

Lindblad, B. A. and Lundstedt, H.: 1981, *Solar Phys.* **74**, 197.

Mavromichalaki, H. and Petropoulos, B.: 1984, *Astrophys. Space Sci.* **106**, 61.

Mavromichalaki, H., Marmatsouri, E., and Vassilaki, A.: 1988a, *Earth, Moon and Planets*, (in press).

Mavromichalaki, H., Vassilaki, A., and Marmatsouri, E.: 1988b, *Solar Phys.* **115**, 345.

Mitchel, J. M.: 1966, *Climatic Change*, WMO No. 195, TP 1000, p. 33.

Nagashima, K. and Morishita, I.: 1980, *Planetary Space Sci.* **28**, 195.

Okhlopkov, V. P., Okhlopkova, L. S., and Charakhchyan, T. N.: 1979, *Geomagnetizm i Aeronomiya* **19**, 287.

Okhlopkov, V. P., Okhlopkova, L. S., and Charakhchyan, T. N.: 1986, *Geomagnetizm i Aeronomiya* **26**, 19.

Otaola, J. A., Perez-Enriquez, R., and Valdes-Galicia, J. F.: 1985, *Proc. 19th Int. Cosmic Ray Conf., La Jolla* **4**, 93.

Pomerantz, M. A. and Duggal, S. P.: 1974, *Rev. Geophys. Space Phys.* **12**, 343.

Sakurai Kunimito: 1979, *Nature* **278**, 146.

Sakurai Kunimito: 1981, *Solar Phys.* **74**, 38.

Shapiro, R. and Ward, F.: 1962, *J. Atmospheric Sci.* **19**, 506.

Simpson, J. A.: 1963, *Proc. 8th Int. Cosmic Ray Conf., Jaipur* **2**, 155.

Xanthakis, J.: 1971, in C. Macris (ed.), *Physics of the Solar Corona*, D. Reidel Publ. Co., Dordrecht, Holland, p. 179.

Xanthakis, J., Mavromichalaki, H., and Petropoulos, B.: 1981, *Astrophys. Space Sci.* **74**, 303.

Xanthakis, J., Poulakos, C., and Petropoulos, B.: 1988, *Astrophys. Space Sci.* **141**, 233.