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ΑΣΤΡΟΝΟΜΙΑ. – **Cosmic-ray intensity related to solar and terrestrial activity indices in solar cycle No 20,** *by J. Xanthakis - H. Mavromichalaki - B. Petropoulos* *. Ἀνεκοινώθη ὑπὸ τοῦ Ἀκαδημαϊκοῦ κ. Ἰωάννου Ξανθάκη.

ABSTRACT

The eleven year modulation of cosmic ray intensity is studied, using data of nine worldwide neutron monitoring stations extended over the period 1965-1975. From this analysis the following relation among the modulated cosmic-ray intensity I, the relative sunspot number R, the number of proton events N_p and the geomagnetic index A_p has been derived which describes the long term modulation of cosmic rays:

$$I = C - 10^{-3} (KR + 4N_p + 12A_p)$$

where C is a constant depending on the rigidity of each station and K is a coefficient related to the diffusion coefficient of cosmic rays and its transition in space. The standard deviation between the observed and calculated by the above relation values of cosmic-ray intensity is about 5 - 9 %. This relation has been explained by a generalization of Simpson solar wind model which has been proved by the spherically symmetric diffusion - convection theory.

* Ι. ΞΑΝΘΑΚΗ - Ε. ΜΑΥΡΟΜΙΧΑΛΑΚΗ - Β. ΠΕΤΡΟΠΟΥΛΟΥ, **Συσχέτισις τῆς ἐντάσεως τῆς κοσμικῆς ἀκτινοβολίας καὶ τῶν ἡλιακῶν καὶ γηίνων δεικτῶν δραστηριότητος διὰ τὸν 20ον ἡλιακὸν κύκλον.**

1. INTRODUCTION

The inverse correlation between cosmic-ray intensity and solar activity in the eleven year variation was first pointed out by Forbush (1958) and has been studied in detail by many researchers (see reviews by Rao, 1972; Pomerantz and Duggal, 1974; Moraal, 1976). According to these studies the time lag between cosmic-ray intensitiy and solar activity varies from several to twelve months, depending on the solar cycle and on the activity index adopted (Balasubrahmanyan, 1969; Dorman et al, 1977). Xanthakis (1971) has found a time lag of one year between cosmic-ray intensity and solar activity index Ia for the solar cycle No 19. Nagashima and Morishita (1980 b) have pointed out that the hysteresis between the solar activity maximum and the cosmic-ray intensity minimum is 9, 1, 10 - 11 and 2 months for each of the solar cycles 17, 18, 19 and 20, respectively. Other indices of solar activity, such as geomagnetic index A_p or coronal green line intensity, appear to reduce the hysteresis effect considerably. Moreover the time lag depends on solar activity (Wang, 1970) and is shorter in the decreasing phase of activity than in the increasing phase (Simpson, 1963). Also it decreases as the cosmic-ray rigidity increases. Recently the hysteresis mode of the Sun's effect on the cosmic-ray flux arriving from the Galaxy to the Earth's orbit has been shown to result from (1) the large size of the modulation region, (2) the variations of the mean sunspot heliolatitude from high to low latitudes throughout the eleven year cycle and (3) the finite time of galactic cosmic ray diffusion to the modulating region, which is essentially a function of particle energy (Dorman and Soliman, 1979).

Studies of long term modulations of cosmic rays in interplanetary space give valuable information about electromagnetic state in the heliomagnetosphere and about the origin of cosmic rays. Thus, a large amount of data concerning the rigidity dependence of long the term variation of cosmic rays and its relationship with other solar and terrestrial parameters have now been used in comparison with various theoretical predictions (Rao, 1972).

In a previous work, Xanthakis (1971) has given a quantitative relation among the cosmic-ray intensity obtained from Mt. Washington station's data the solar activity index Ia and the number of proton flares N_{PF} for the 19^{th} solar cycle. Chirkov aud Kuzmin (1979) have shown that the 11-year cosmic-ray intensity I_{PW} from data of ionization chamber in Yakutsk for the 19^{th} and 20^{th} solar cycles, can be expressed by the following expression:

$$I_{PW}(\%) = -0.008\,W - KC_i + A\,, \qquad (1)$$

where W is the Wolf number, C_i the geomagnetic index and K and A are constants dependent on the solar cycle. Recently Nagashima and Marishita (1980b) have also used the sunspot number R and the geomagnetic index AA in order to compute the modulated cosmic-ray intensity.

In this work it is proposed to find a general relationship between the intensity of galactic cosmic rays and the most appropriate solar and terrestrial activity indices which are influenced by the cosmic-ray modulation. For this purpose we have taken account the following indices: the relative sunspot number R, the number of proton events N_p and the geomagnetic activity index A_p. This relation will be interpreted from a generalization of Simpson's coasting solar wind model (1963).

2. DATA ANALYSIS AND RESULTS

In order to study the long-term modulation in cycle No 20, data of cosmic-ray intensities have been used from nine neutron monitoring stations (super NM-64) extending over the period 1965-1975. The altitude, the geographic coordinates and the cut-off rigidity of each station are listed in table I. The corrected for pressure data for each station were normalized by the method

$$\frac{Ii - Imin}{Imax - Imin}\,,$$

where I min and I max are, respectively, the minimum and the maximum intensities of cosmic rays during the 20^{th} solar cycle and Ii is the corresponding half-year value of cosmic-ray intensity. With this method the intensities at the solar minimum 1965 are taken equal to 1.00 and at the solar maximum 1969 are taken equal to zero.

T A B L E I

Stations whose data have been utilized in this analysis.

Station (Super NM - 64)	Height (m)	Geographic Latitude (deg)	Coord. Longitude (deg)	Threshold Rigidity (GV)
Alert	57	82.50 N	62.33 W	0.00
Thule	260	76.60 N	68.80 W	0.00
Mc Murdo . .	48	77.90 S	166.60 E	0.01
Inuvik	21	68.35 N	133.72 W	0.18
Goose Bay . .	46	53.27 N	60.40 W	0.52
Deep River .	145	46.10 N	77.50 W	1.02
Kiel	54	54.30 N	10.10 E	2.29
Hermanus . .	26	34.42 S	19.22 E	4.90
Pic du Midi .	2860	42.93 N	0.25 E	5.36

For this analysis the semi-annual number of significant solar proton events N_p (Solar-Terrestial Physics and Meteorology, 1977 ; 1979) and the half-year averages of relative sunspot number R (Zürich Observatory) and geomagnetic index A_p have also been used.

A detailed study of all these data led us to a new generalized empirical relation. Accordingly to this the cosmic-ray intensity which is observed in the Earth (modulated intensity) on a semi-annual basis can be calculated from the difference between a constant function C and the sum of the most important solar and terrestrial indices which are affected cosmic-ray modulation. This expression, taking into account the indices R, N_p and A_p , is the following:

$$I = C - 10^{-3}(KR + 4N_p + 12A_p) \qquad (2)$$

where C is a constant that depends linearly from cut-off rigidity of each station and K is a coefficient which is also rigidity-dependent and is probably related to the diffusion coefficient of cosmic rays and its transition in space. The physical properties in the modulating region derived from the constant C and the coefficient K are discussed below, while the numerical values of them are given for each station in table II.

The observed neutron monitoring, data of each station I_{obs} and the corresponding I_{cal} values calculated from equation (2), are given in table III. The 11-year variation of these values is shown in Fig. 1. The continuous line represents the observed cosmic-ray intensity I_{obs} and the dashed line gives the corresponding calculated value I_{cal}. It is worth mentioning that the agreement between measured and calculated by equation (2) cosmic-ray intensities for all used here neutron monitoring stations is very good. The standard deviation between the observed and calculated values of cosmic-ray intensity is of the order of 5 - 9%.

If we substract I_{cal} from I_{obs}, the difference $\Delta(I_{obs} - I_{cal})$ should be independent of the eleven-year and short term variations. Practically, however, the difference $\Delta(I_{obs} - I_{cal})$ in Fig. 2 still shows remarkable short term variations, especially during the years 1965-1966 due, perhaps, to the incomplete elimination by the present indices.

Examining the above relation (2) and applying this to the nine ground based stations of cosmic rays we observed that so the constant

TABLE II

Values of the constant C and the coefficient K for each of the neutron monitor stations which have been used in this work.

Station	C	K
Alert	C = 0.93	K = 5.0, 1965 I - 1967 II
		$K = 5.0 + 2.0 \sin \frac{\pi}{6} t$, 1968 I (t = 0) - 1971 II (t = 7)
		K = 0.0, 1972 I - 1975 II
Thule	C = 0.93	K = 4.0, 1965 I - 1968 I
		$K = 7.0 - 0.5 \sin \frac{\pi}{2} t$, 1968 II (t = 0) - 1971 I (t = 5)
		K = 0.0, 1971 II - 1975 II
Mc Murdo. . . .	C = 0.94	K = 2, 1965 I - 1966 I, 1971 II - 1975 II
		K = 4, 1966 II - 1967 II
		$K = 5 + 2 \sin^2 \frac{\pi}{6} t$, 1968 I (t = 0) - 1971 I (t = 6)

Table II (continued)

Station	C	K
Inuvik	C = 0.94	K = 1.5, 1965 I - 1966 I, 1971 II - 1975 II
		$K = 1.5 + 5.4 \sin \frac{\pi}{12} t$, 1966 II (t = 0) - 1771 I (t = 9)
Goose Bay . . .	C = 0.95	K = 1.9, 1965 I - 1966 I, 1971 II - 1975 II
		$K = 1.9 + 4.8 \sin \frac{\pi}{12} t$, 1966 II (t = 0) - 1971 I (t = 9)
Deep River . . .	C = 1.02	K = 1.9, 1965 I - 1966 I, 1971 II - 1975 II
		$K = 1.9 + 5.7 \sin \frac{\pi}{12} t$, 1966 II (t = 0) - 1971 I (t = 9)
Kiel	C = 1.09	K = 5.5, 1965 I - 1968 I, 1973 II - 1975 II
		$K = 7.7 + 0.7 \cos \pi t$, 1968 II (t = 0) - 1971 I (t = 5)
		$K = 5.5 - 3.5 \sin \frac{\pi}{4} t$, 1971 II (t = 0) - 1973 I (t = 4)

Table II (continued)

Station	C	K
Hermanus . . .	C = 1.27	$K = 10.0 - 2.5 \sin \frac{\pi}{6} t$, 1965 II (t = 0) - 1968 II (t = 6)
		$K = 10.0 - \sin^2 \frac{\pi}{2} t$, 1968 II (t = 0) - 1970 II (t = 4)
		$K = 10.0 - 6 \sin \frac{\pi}{4} t$, 1971 I (t = 0) - 1975 I (t = 8)
		K = 10.0, 1965 I, 1975 II
Pic du Midi . .	C = 1.30	$K = 10.0 + 4.5 \sin \frac{\pi}{4} t$, 1964 II (t = 0) - 1968 II (t = 8)
		K = 10, 1969 I - 1970 II,
		$K = 10.0 - 4.5 \sin \frac{\pi}{4} t$, 1971 I (t = 0) - 1975 I (t = 8)

T A B L E III

The percented values of the intensity of cosmic-rays, measured, Iobs, and calculated by the relation (2), Ical.

	ALERT		THULE		McMURDO		INUVIK		GOOSE BAY	
	Iobs (%)	Ical (%)	Iobs (%)	Ical (%)	Iobs (%)	Ical (%)	Iobs (%)	Ical (%)	Iobs (%)	Ical (%)
1965 I			1.00	0.77	1.00	0.87	1.00	0.83	1.00	0.83
II	1.00	0.76	0.95	0.78	0.98	0.88	0.96	0.82	0.94	0.83
1966 I	0.87	0.64	0.83	0.68	0.86	0.91	0.89	0.78	0.85	0.78
II	0.58	0.48	0.54	0.54	0.58	0.55	0.62	0.69	0.58	0.68
1967 I	0.44	0.31	0.35	0.40	0.40	0.41	0.48	0.50	0.43	0.49
II	0.34	0.28	0.33	0.37	0.34	0.38	0.36	0.35	0.25	0.36
1968 I	0.25	0.20	0.26	0.31	0.21	0.21	0.28	0.19	0.25	0.19
II	0.02	0.09	0.00	-0.01	-0.01	0.10	0.03	0.08	0.04	0.10
1969 I	0.00	-0.05	0.00	-0.02	0.00	-0.04	0.00	-0.04	0.00	-0.01
II	0.02	0.08	0.03	0.08	0.06	0.09	0.03	0.10	0.02	0.13
1970 I	0.04	0.00	0.03	-0.10	0.04	0.01	0.07	0.01	0.02	0.04
II	0.02	0.18	0.09	0.09	0.10	0.20	0.08	0.18	0.06	0.20
1971 I	0.28	0.49	0.39	0.40	0.50	0.50	0.42	0.48	0.34	0.49
II	0.61	0.48	0.77	0.79	0.82	0.95	0.66	0.68	0.60	0.66
1972 I	0.77	0.67	0.76	0.67	0.82	0.83	0.68	0.57	0.52	0.55
II	0.71	0.75	0.74	0.75	0.81	0.88	0.67	0.67	0.57	0.65
1973 I	0.65	0.68	0.66	0.68	0.71	0.78	0.59	0.62	0.49	0.61
II	0.78	0.77	0.80	0.77	0.92	0.84	0.78	0.74	0.68	0.73
1974 I	0.75	0.71	0.71	0.71		0.78	0.72	0.68	0.60	0.67
II	0.61	0.68	0.67	0.68		0.76	0.57	0.63	0.48	0.62
1975 I	0.76	0.74	0.73	0.74		0.77	0.72	0.73	0.64	0.74
II	0.80	0.78	0.77	0.78		0.83	0.77	0.76	0.65	0.76

		DEEP RIVER Iobs (%)	DEEP RIVER Ical (%)	KIEL Iobs (%)	KIEL Ical (%)	HERMANUS Iobs (%)	HERMANUS Ical (%)	PIC DU MIDI Iobs (%)	PIC DU MIDI Ical (%)
1965	I	1.00	0.89	1.00	0.91	1.00	1.03	1.00	1.01
	II	0.92	0.90	0.91	0.91	0.94	1.02	0.85	0.99
1966	I	0.86	0.85	0.82	0.79	0.88	0.85	0.77	0.72
	II	0.57	0.74	0.55	0.61	0.61	0.66	0.52	0.56
1967	I	0.44	0.54	0.43	0.43	0.48	0.43	0.42	0.52
	II	0.37	0.39	0.34	0.38	0.32	0.34	0.37	0.59
1968	I	0.30	0.20	0.28	0.31	0.24	0.14	0.27	0.38
	II	0.03	0.09	0.03	0.00	0.03	0.01	0.04	0.04
1969	I	0.00	-0.04	0.00	0.07	0.00	0.03	0.00	-0.06
	II	0.03	0.11	0.04	0.10	0.11	0.12	0.10	0.15
1970	I	0.06	0.00	0.06	0.12	0.13	0.07	0.12	-0.01
	II	0.08	0.20	0.08	0.12	0.15	0.15	0.16	0.18
1971	I	0.46	0.53	0.45	0.54	0.49	0.55	0.51	0.58
	II	0.77	0.73	0.70	0.71	0.72	0.68	0.71	0.63
1972	I	0.79	0.62	0.73	0.68	0.82	0.71	0.66	0.63
	I	0.75	0.72	0.68	0.72		0.74	0.64	0.70
1973	I	0.70	0.69	0.60	0.59		0.57	0.54	0.60
	II	0.89	0.80	0.76	0.77		0.68	0.72	0.75
1974	I	0.79	0.74		0.69		0.54		0.62
	II	0.64	0.70		0.64		0.50		0.57
1975	I	0.85	0.81		0.84		0.98		1.01
	II	0.89	0.83		0.83		0.92		0.95

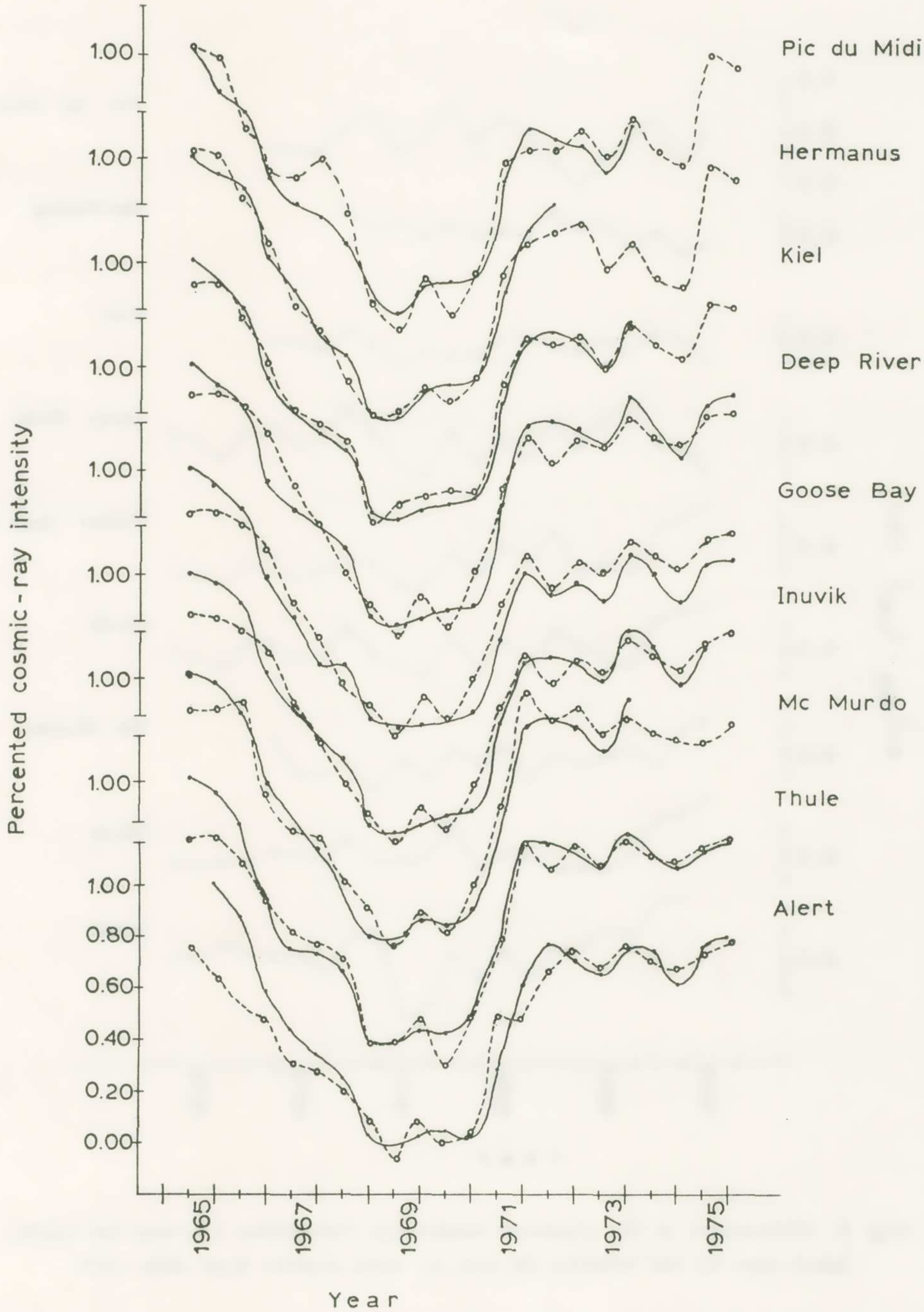

Fig. 1. The 11-year variation of cosmic ray intensity for each station is given. The continuous line represents the observed cosmic-ray intensity I_{obs} and the dashed line gives the corresponding, calculated by the relation (2), value Ical.

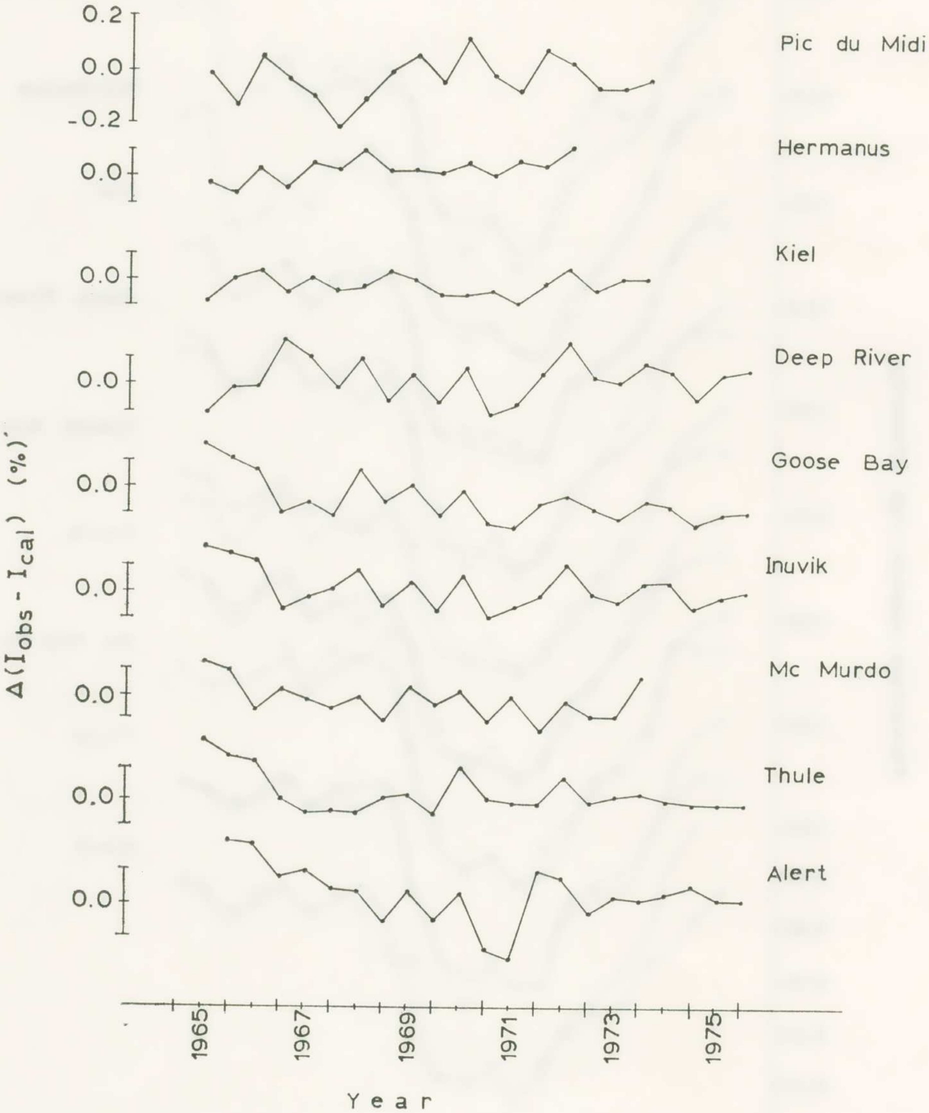

Fig. 2. Differences of the observed cosmic-ray intensities I_{obs} and the calculated ones by the relation (2) Ical for each station from 1965 - 1975.

C as the mean value of the coefficient K ($\overline{K}$) are linearly correlated with the cut-off rigidity of each station for the 20th solal cycle. The variation of C and $\overline{K}$ versus the rigidity of the stations are presented in Fig. 3. A

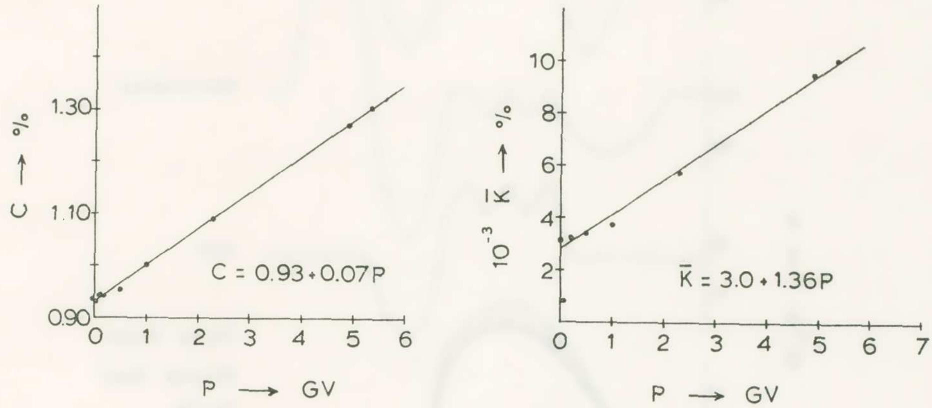

Fig. 3 Rigidity dependence of the constant C and of coefficient K for the time interval 1965 - 1975.

small discrepancy from the linear correlation was shown in the value of $\overline{K}$ from the McMurdo neutron monitor. From this Figure the following close relations are concluded :

$$C = 0.93 + 0.07\,P \tag{3}$$

$$\overline{K} = 3.00 + 1.36\,P \tag{4}$$

where P is the cut-off rigidity of each station. From an off-hand point of view, the coefficient K is a quantity of the modulation of cosmic rays travelling through the interplanetary space with the solar wind. The time dependence of semi-annual values of this coefficient for each station is given in Fig. 4.

It is interesting to remark that the coefficient K has a constant value for the first years of the ascending branch of solar activity and for the 3 - 4 last years of the descending branch, while for the maximum of solar activity it has a period of 4 - 6 years and can be presented by the relation :

$$K = a + b \sin \frac{2\pi}{Q}\, t \tag{5}$$

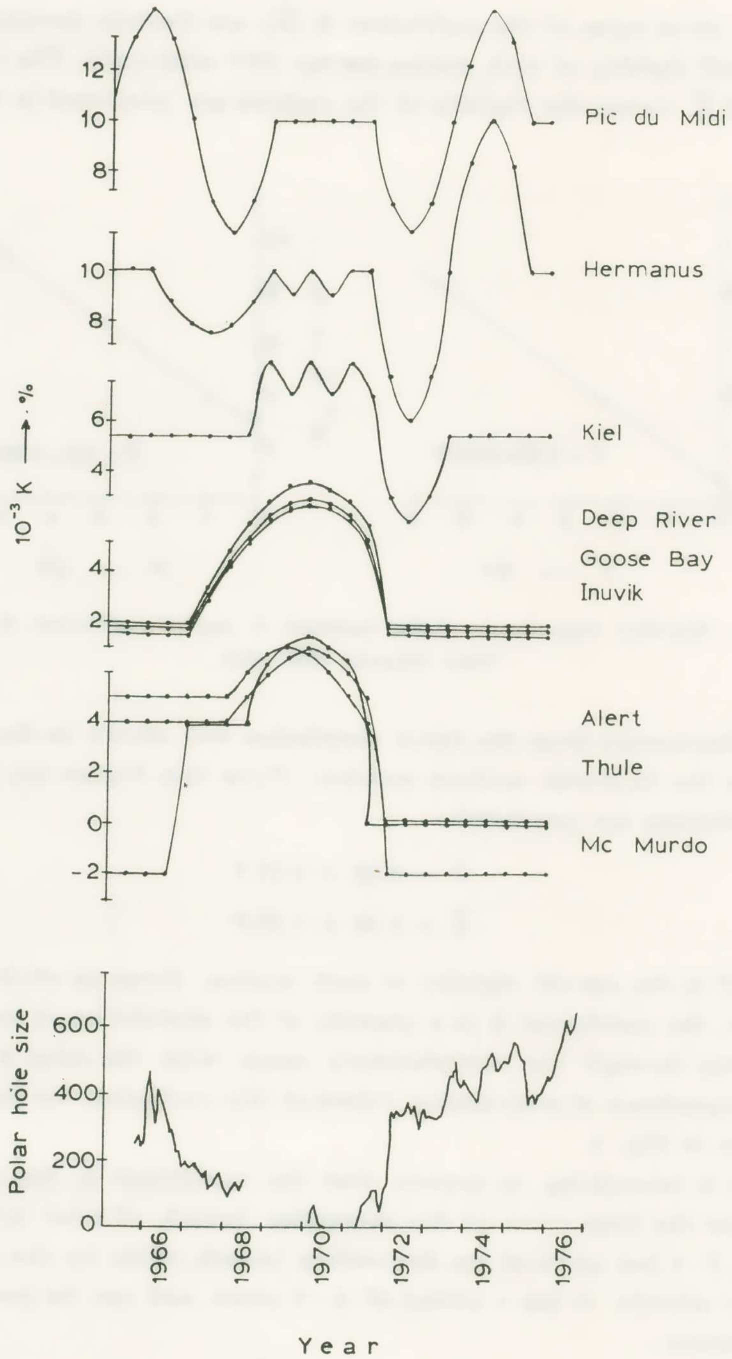

Fig. 4. Time dependence of semi-annual values of coefficient K for each station. Also, the variation of polar hole size versus time is presented for the time interval 1965 - 1975.

where a, b are constants given in table II for each station. It is noted that the stations with cut-off rigitities $\geqq$ 2.20 GV in which there is a smaller modulation of cosmic rays, here appears to be a multiple frequency variation of K, which probably can be resulted from the wide asymptotic cones of acceptance of these stations introduced slight variations with a period of 2 - 3 years.

In the stations with low energies P $\leqq$ 2.20 GV the curve of K is in inverse correlation with the curve of size of «polar coronal holes», as it is presentend in Fig. 4 (Hundhausen et al, 1980). As was pointed out recently, there is a close correspondence between the polar hole size and the cosmic-ray intensity variations. This suggests the influence of a three dimensional interplanetary structure on the propagation of cosmic rays through the solar system to the orbit of Earth. It is known that coronal holes are associated with magnetic field lines that open into interplanetary space and have been identified as the cource of the major streams of fast solar wind in interplanetary space. Coronal holes also play a key role in determining the spatial structure of the interplanetary magnetic field. So, it is well connected the variation of coefficient K with the size of coronal holes and, consequently with the structure and variations of the interplanetary magnetic field.

3. SOME CHARACTERISTICS OF THE ELEVEN YEAR VARIATION OF COSMIC-RAY INTENSITY OF THE 20th SOLAR CYCLE

A detailed examination of the Figs. 1 and 2 and of the 11-year variation of cosmic rays reveals the following features:

The shape on the variation of cosmic-ray intensity over the 20th solar cycle bears a close relationship to the actual solar activity cycle. The two maxima first postulated by Gnevyshev (1967) in a solar cycle also seem to be detectable in cosmic rays also during this solar cycle. The cosmic-ray intensity appears two minima: the first one is appeared in 1969 which happens with the main maximun of solar activity and the second one is appeared in the end of 1971 (Krivsky and Ruzicková - Topolová, 1978). The rapid reappearance of the polar holes between late 1970 and early 1971 following their disappearance in the sunspot maximum, has been justified by the second minimum of cosmic rays. This is resulted by the fact that the temporal variations in the size of the polar holes correspond to those in the cosmic ray intensity observed at the Earth (Hundhausen et al, 1980). Between the two minima of cosmic-rays polarity reversal of the magnetic field of the Sun because of the 22-year variation is occured. The polarity reversal took place in the southern hemisphere in mid-1969 and ended in Aug. 1971 when the northern hemisphere completed its reversal.

It is noteworthy that the amplitude of the modulation in the examined solar cycle is smaller than the corresponding in the 19th cycle. Also the correlation of the cosmic-ray intensity variations with solar activities is poor compared with the previous solar cycles (Ashirof et al, 1977). Moreover some anomalous phenomena in the modulation of cosmic rays have been observed for several years after the solar maxima such as the abnormality of the modulation rigidity spectra of cosmic-ray intesities (Lockwood and Webber, 1979), the sudden recovery of the intensity (Kuzmin et al, 1977) etc. Recently many researchers have pointed out that all these strange features at the 20th cycle could be explained by the superposition of 22-year and 11-year modulations. It is noted that the rigidity spectra of these two modulations are different from each other (Charakhchyan et al, 1977) and the 22-year modulation is independent of solar activity, except for its transition period (Ashirof et al, 1977).

It is mentioned that the time lag between cosmic rays and solar activity in the 20th solar cycle is not significant. It is only 2 months (Nagashima and Morishita, 1980b). So the hysteresis effect appears to have been reduced considerably in this solar cycle.

4. DISCUSSION AND THEORETICAL INTERPRETATION OF THE RELATION (2)

It is well known that the solar-cycle modulation of the propagation of cosmic rays entering the solar system from interstellar space has been attributed to their interaction with a solar wind that varies with solar activity. A detailed theory of such effects of scattering of cosmic rays by irregularities in the magnetic field convected along by the solar wind has been developed (Parker, 1963; Jokipii and Parker, 1970). The diffusion-convection and adiabatic deceleration theory (Gleeson and Axford, 1967) of galactic cosmic rays into a spherically symmetric solar wind with this scattering would lead to an eleven year variation. In the light of this theory, the modulations are well explained by setting proper physical states in the modulating region, but it is not so clear how the states are related to solar activities.

Iucci et al (1975) tried to obtain a dynamic relation of the modulation of cosmic rays to solar activity, assuming the following two mechanisms. One is on outward-sweep-away mechanism from the Sun due to the flare activity that causes a depression of the cosmic-ray density. The other is a diffusion mechanism which causes a recovery of the density.

Contrary to Iucci et al, whose model treats the modulation as non-stationary, the coasting solar wind model (Simpson, 1963) interprets it as a variation in quasi-stationary state. With this concept it is assumed that disturbances due to solar activities continue to affect cosmic rays while travelling through the modulating region with the solar wind. In other words, the intensity of cosmic rays at a time t is affected by all the activities produced from the Sun before the specified time t. Accordingly, the modulation can be described by the following integral equation which is derived from a generalization of Simpson's coasting solar wind model (1963) :

$$I(t) = I_\infty - \int_0^\infty f(r)\, S(t-r)\, dr\,, \tag{6}$$

where I_∞ and $I(t)$ are, respectively, the galactic and modulated cosmic-ray intensities, $S(t-r)$ is the source function representing some proper solar activity index at a time $t-r$ $(r \geqq 0)$ and $f(r)$ is the characteristic function which expresses the time dependence of an efficiency depression due to solar disturbances represented by $S(t-r)$, when the disturbances propagate through the modulating region with the solar wind. It is noteworthy that as Nagashima and Morishita (1980a) have proved out, this equation can also be derived from the spherically symmetric diffusion-convection theory, including the Compton-Getting factor (Gleeson and Axford, 1967) on some assumptions, and the source and characteristic function can acquire new physical meanings which are related to the diffusion coefficient of cosmic-rays and its transition is space. Nagashima and Morishita (1980 a) have shown that the modulations can be described by the source function which is expressed by the following linear combination of two indices one is the sunspot number R and the other the geomagnetic activity index AA substituted for such stream-like disturbances as coronal holes (Murayama and Hakamada, 1975):

$$f(r)\,S(t-r) = f_R(r)\,R(t-r) + f_A(r)\,AA(t-r) \tag{7}$$

In this work the dependences of the modulations and of their surroundings of solar activity are studied by a new method, using data of cosmic-ray intensities from ground based stations well distributed in latitude. According to this analysis it is proposed that the modulations ought to be expressed by the linear combination of three indices, one is the sunspot number R, second is the number of proton events and third is the geomagnetic activity A_p:

$$f(r)\,S(t-r) = f_R(r)\,R(t-r) + f_N(r)\,N_p(t-r) + f_A(r)\,A_p(t-r) \tag{8}$$

The time lag r between solar activity and cosmic-ray intensity in the examined solar cycle is approximately $\leqq 2$ months (Nagashima and Morishita, 1980 a). This time can be neglected in relation (8) because of using half-year values of all indices in the present analysis. Substituting the equation (8) into the general equation of Simpson model and indentifying with the empirical relation (2) we get:

$$I_\infty = C = 0.93 + U \tag{9}$$

$$\int_0^\infty f_R(r)\,dr = k \cdot 10^{-3} \tag{10}$$

$$\int_0^\infty f_N(r)\,dr = 4 \cdot 10^{-3} \tag{11}$$

$$\int_0^\infty f_A(r)\,dr = 12 \cdot 10^{-3} \tag{12}$$

where U expresses the modulation of the galactic cosmic ray intensity I_∞ due to the cut-off tigidity of each station. It is observed that the characteristic function f (r) of the N_p and A_p has a constant value during the 20th solar cycle, while the f (r) distribution of the index R has a complex behaviour (section 2).

In order to explain this behaviour it is purposed that the existence of 22-year variation affectes the 11-year cosmic modulation, as it is obvious in Fig. 1. At the end of 1971 the cosmic ray intensity appears a sudden recovery to the predecrease level which happens one year behind the polarity reversal of the polar magnetic field of the Sun. This time lag r can be explained on the basis of Simpson's model and the general diffusion-convection theory and expressed by two characteristic times as follows:

$$r = r_{cs} + r_{DC} \tag{13}$$

where r_{cs} is the time required for galactic cosmic rays to recognize the polarity reversal at the modulation boundary after the occurence of the reversal at the solar surface, and r_{DC} is the time required for galactic cosmic rays to reach the Earth through the diffusion-convection process after receiving the information at the boundary (22 days for neutrons with $P = 1.5$ GV). If we accepte the relation (13) and the experimental equation (4) the characteristic function of sunspot number R can be written:

$$\int_0^\infty f_R(r_{cs})\, dr_{cs} + \int_0^\infty f_r(r_{DC})\, dr_{DC} = (3.0 + 1.36\, P)\, F(t) \cdot 10^{-3} \tag{14}$$

Where F (t) is a function of time.

From this analytical expression we find that

$$\int_0^\infty f_R(r_{cs})\, dr_{cs} = 3F(t) \cdot 10^{-3} \tag{15}$$

$$\int_0^\infty f_R(r_{DC})\, dr_{DC} = 1.36\, P \cdot F(t) \cdot 10^{-3} \tag{16}$$

Note that the characteristic function of sunspot number R reported to the characteristic time r_{cs} is independent of terrestrial parameters by definition of the time r_{cs}. So the function F(t) is not related with the rigidity of ground measured particles and othe terrestrial indices. Contradictory, the characteristic function of R reported to the time r_{DC} is dependent on the rigidity P of the particles and the function F (t), which can be related to solar and interplanetary parameters. Because of the definition of the time r_{DC}, the function F (t) can be well related to the diffusion process of cosmic rays and its transition in interplanetary space.

As Nagashima and Morishita (1980a) have shown, the function f (r) is inversely propotional to the transition of the diffusion coefficient due to the magnetic disturbances carried on the solar wind. It is known that the diffusion coefficient is related to magnetic fluctuations $\overline{\Delta H}$ in the modulating region. Their mutual relation is not so simple (Jokipii, 1967; 1968) but if we could assume that the diffusion coefficient is inversely proportional to $\overline{\Delta H}$, we obtain the fluctuations conversely from the observed coefficient. Consequently, $\overline{\Delta H}$ is assumed to be proportional to the function f (r) and also to coefficient K which is given by relation (2). Indeed it was experimentally confirmed in the present work by the Figure 3 that the coefficient K is in inverse relation with the size of polar coronal holes. This correlation was poor for stations with cut-off rigidities > 2.20 GV (Hundhausen et al., 1980). As it has been shown by King (1976), the yearly averaged magnitudes of positive and negative polarity magnetic field vectors show separate solar cycle variations which are in inverse correlation with the variation of polar coronal holes size. From all these it is resulted that the characteristic function $f_R(r)$ and consequently, the coefficient K gives information upon the diffusion coefficient of cosmic-rays.

5. CONCLUSIONS

From all the above analysis and discussion we conclude the following:

The existence of the 11-year modulation of cosmic-ray intensity in the 20^{th} solar cycle is pointed out, using data of nine worldwide neutron monitor stations over the period 1965 - 1975. Some anomalous phenomena are appeared in this solar cycle such as the poor correlation of cosmic-ray intensity and solar activity, the sudden recovery of intensity, the small time lag between cosmic-ray intensity and solar activities etc. These phenomena are associated with polarity reversal of the polar magnetic field of the Sun which occurs around the solar maximum. So the modulation of cosmic-ray intensity is the result of the superposition of 22-year and 11-year modulations.

A fundamental equation which describes the long term modulation of the cosmic-ray intensity is given in this work. According to this relation 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 constant C and coefficient K. The constant C has a constant value for each station, which is rigidity dependent and the coefficient K is mainly responsible for the 11-year modulation of cosmic-rays. For low rigidities ($P \leqslant 2.20$ GV) this coefficient can be inversely correlated to the polar coronal holes size.

The above mentioned relation is well explained by the generalized Simpson's solar wind model where the constant C has a physical meaning and the coefficient K is related to the diffusion coefficient of cosmic-rays and its transition in space.

In conclusion, it is noteworthy that the analytical method which utilizes the empirical relation (2) is useful for the study of the long term modulation of cosmic-rays. Owing to the method used, one could reproduce to a certain degree the modulation with the proper source function (R, N_p, A_p) and could also associate the source function with the electromagnetic properties in the modulating region (K). Therefore, it is necessary to search for a more suitable source function among various kinds of solar activity indices or physical quantities.

In the future a further study of these parameters with a variety of phases or lag times, perhaps with observations out of the ecliptic plane, will lead us to a better understanding of the relations among coronal structure, interplanetary structure and cosmic-rays in the solar system.

ΠΕΡΙΛΗΨΙΣ

Πρῶτος ὁ Forbush (1958) ἔδειξε ὅτι ἡ ἔντασις τῆς κοσμικῆς ἀκτινοβολίας ποὺ μετρᾶται εἰς τὸ ἔδαφος εὑρίσκεται εἰς ἀρνητικὴν συσχέτισιν μὲ τὸν δείκτην τῆς ἡλιακῆς δραστηριότητος R (σχετικὸν ἀριθμὸν κηλίδων (δείκτη τῆς Ζυρίχης)).

Εἰς μίαν προγενεστέραν ἐργασίαν ὁ κ. Ξανθάκης (1971) ἔδωσε μίαν ἀναλυτικὴν σχέσιν, ἡ ὁποία συνδέει τὴν ἑξαμηνιαίαν ἔντασιν τῆς κοσμικῆς ἀκτινοβολίας τοῦ σταθμοῦ τῆς Washington μὲ τὸν δείκτην τῆς ἡλιακῆς δραστηριότητος Ia (δείκτην τῶν ἐμβαδῶν) καὶ τὸν ἀριθμὸν τῶν ἡλιακῶν ἐκλάμψεων τῶν πρωτονίων. Ἡ σχέσις αὐτὴ εὑρέθη ὅτι ἰσχύει διὰ τὸν 19ον ἡλιακὸν κύκλον μὲ διαφορὰν φάσεως μεταξὺ τῆς ἐντάσεως τῆς κοσμικῆς ἀκτινοβολίας καὶ τοῦ δείκτου R, ἑνὸς περίπου ἔτους. Κατὰ τὸ παρελθὸν ἔτος ὁ Chirkov καὶ Kuzmin, ἔδωσαν μίαν ἀναλυτικὴν σχέσιν μεταξὺ τῆς ἐντάσεως ποὺ ἐμετρήθη εἰς τὸν σταθμὸν τοῦ Yakutsk διὰ τὸν 19ον καὶ 20ὸν κύκλον ἀφ᾽ ἑνὸς καὶ τοῦ ἀριθμοῦ Wolf, (δείκτου τῆς ἡλιακῆς δραστηριότητος) καὶ τοῦ γεωμαγνητικοῦ δείκτου τοῦ σταθμοῦ ἀφ᾽ ἑτέρου.

Εἰς τὴν παροῦσαν ἐργασίαν προκειμένου νὰ δώσωμε μίαν γενικωτέραν σχέσιν μεταξὺ τῆς ἐντάσεως τῆς κοσμικῆς ἀκτινοβολίας, ποὺ μετρᾶται εἰς τὸ ἔδαφος ἀφ᾽ ἑνὸς καὶ τῶν διαφόρων ἡλιακῶν καὶ γεωμαγνητικῶν δεικτῶν ἀφ᾽ ἑτέρου ἐμελετήσαμε τὴν ἑνδεκαετῆ διαμόρφωσιν τῆς ἐντάσεως τῆς κοσμικῆς ἀκτινοβολίας διὰ τὴν περίοδον 1965 - 1975 (20ος ἡλιακὸς κύκλος), χρησιμοποιώντας τὰ δεδομένα ἐννέα σταθμῶν διαφόρου γ. πλάτους. Εὑρέθη δὲ ὅτι ἡ ἔντασις τῆς κοσμικῆς ἀκτινοβολίας I καὶ τῶν ἐννέα αὐτῶν σταθμῶν δύναται νὰ ὑπολογισθῇ ἐκ τῆς σχέσεως:

$$I = C - 10^{-3}(KR + 4N_p + 12A_p)$$

ὅπου C, καὶ K (μέτρον τοῦ K) σταθεραὶ ἐξαρτώμεναι γραμμικῶς ἐκ τῆς γεωμαγνητικῆς δυσκαμψίας τοῦ σταθμοῦ, R: ὁ δείκτης τῶν ἡλιακῶν κηλίδων (δείκτης τῆς Ζυρίχης) ποὺ ἐκφράζει τὴν ἡλιακὴν δραστηριότητα, N_p: ὁ ἀριθμὸς τῶν γεγονότων ποὺ προεκάλεσαν τὰ πρωτόνια, A_p: ὁ γεωμαγνητικὸς δείκτης ἢ δείκτης τοῦ Bartel. Ἡ χρονικὴ καθυστέρησις μεταξὺ τοῦ δείκτου R καὶ τῆς ἐντάσεως τῆς κοσμικῆς ἀκτινοβολίας εὑρέθη περίπου 2 μῆνες διὰ τὸν 20ον κύκλον.

Αἱ ὑπολογισθεῖσαι ἐντάσεις βάσει τῆς ἀνωτέρω σχέσεως διαφέρουν τῶν μετρηθεισῶν κατὰ 5% - 9%. Προκειμένου νὰ δοθῇ μία φυσικὴ ἐξήγησις τῆς

ἀνωτέρω ἐμπειρικῆς σχέσεως, ἐχρησιμοποιήσαμεν τὸ πρότυπον ἡλιακοῦ ἀνέμου τοῦ Simpson, τὸ ὁποῖον ἐγενικεύσαμε διὰ τοὺς τρεῖς δείκτας R, N_p, A_p. Εὑρέθη οὕτω ἀνάλογος πρὸς τὴν ἐμπειρικὴν σχέσιν μία θεωρητικὴ σχέσις μεταξὺ τῶν I, R, N_p καὶ A_p καὶ ἀπεδείχθη ὅτι ὁ συντελεστὴς C παριστᾶ τὴν γαλαξιακὴν ἀκτινοβολία ἐνῶ ὁ συντελεστὴς K ἐξαρτᾶται ἐκ τῆς μεταβολῆς τῆς ἐκτάσεως τῶν πολικῶν στεμματικῶν ὀπῶν, καὶ ἀπὸ τὴν γεωμαγνητικὴν δυσκαμψίαν.

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