ON REPRODUCTION OF LONG-TERM COSMIC-RAY MODULATION AS SEEN BY NEUTRON MONITOR STATIONS

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Abstract. The dependence of cosmic-ray intensity on 21st solar cycle phenomena has been studied using monthly cosmic-ray values from nine world wide Neutron Monitoring Stations.

For this purpose the long-term cosmic-ray modulation is modelled by treating the most appropriate source functions among various solar, interplanetary and terrestrial activity indices as the input and the cosmic-ray intensity as the output of a linear system taking into account the corresponding time-lag. In this way the modulated galactic cosmic-ray intensity has been reproduced to a certain degree as the cosmic-ray variations follow the observations with a standard deviation of $\sim$ 10%. Still remaining short-term variations in all stations with periods of 2.7 and 3.7 months can possibly be related to the galactic origin of cosmic-rays.

The Simpson solar wind model improved by the spherically symmetric diffusion-convection theory can describe our proposed method.

1. Introduction

As it is known the long term modulation of cosmic-rays observed on the Earth and in its vicinity outside the magnetosphere is approximately in antiphase with the solar activity cycle with some time-lag (Forbush, 1954; 1958). The existence of this cycle variation has been confirmed by many studies of the cosmic-ray record although its origin is not fully understood.

One of the outstanding problems of heliospheric research is to explain the existence of this 11-year variation, that is to determine how solar activity couples to the interplanetary phenomena that produce the long term cosmic-ray modulation. A great effort is carried out to find these relations and to express this variation of galactic cosmic-ray intensity by appropriate solar, interplanetary and terrestrial indices. Such solar flares have been used by Hatton (1980); the geomagnetic index was used by Chirkov and Kuzmin (1979) and others. Nagashima and Morishita (1980) suggested that the long-term modulation is an integral effect of "propagating disturbances" related to the sunspot number which can be described by the diffusion convection theory.

Burlaga (1987) observed a relation between changes in the cosmic-ray intensity and the magnetic field intensity from 1981 to 1985 which is well explained by any model of cosmic-ray modulation. Kota and Jokipii (1991) considered the modulation of cosmic-rays by corotating interaction regions attributing the 11-year variation to changes in the configuration of the heliospheric current sheet.

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TABLE I

Altitude, geographic coordinates, rigidity and values of the constant C for the stations whose data have been utilized in this analysis.

Station (super NM-64)	Height (m)	Geographic latitude (deg)	Ceographic longitude (deg)	Threshold rigidity (eV)	Constant C
Alert	57	72.50N	62.33W	0.00	0.95
Inuvik	21	68.35N	133.72W	0.18	0.95
Goose Bay	46	53.27N	60.40W	0.52	0.93
Deep River	145	46.10N	77.50W	1.02	0.95
S. Antarctica	52	70.30N	2.35W	1.06	0.96
Kiel	54	54.30N	10.10E	2.29	0.96
Hermanus	26	34.42N	19.22E	4.90	0.98
Potchefstroom	1351	26.68S	27.92E	7.30	1.02
Tokyo	20	35.45N	139.43E	11.61	0.99

On the other hand, Lockwood and Webber (1984) found a close relationship between the magnitude and frequency of Forbush decreases and the 11-year cosmic-ray variation; they concluded that the effect of Forbush and other transient decreases is a dominant factor in the long term intensity modulation.

In some previous works of Xanthakis *et al.* (1981), Mavromichalaki and Petropoulos (1987) and Mavromichalaki *et al.* (1990), a relation was expressed between the modulated cosmic-ray intensity for the 19th and 20th solar cycles and some appropriate selected solar and geophysical parameters. This relation was well explained by a generalization of Simpson solar wind model proved by the spherically symmetric diffusion-convection theory.

In this paper we attempted to reproduce the long-term cosmic-ray modulation for the 21st solar cycle taking into account the influence of the relative sunspot number R_z, the solar flares N_f ($\geq 1B$), the solar wind streams S and the geomagnetic index A_p with their time-lag. This method applied successfully to nine ground-based stations which detected cosmic-rays well distributed over the Earth for the time period 1975–1985 is well established in the study of cosmic-ray modulation.

2. Data Analysis

In order to study the modulation character of cosmic-rays for the 21st solar cycle, monthly cosmic-ray data from nine Neutron Monitoring Stations (Super NM-64) extending over the period 1975–1985 have been used. The altitude, the geographic coordinates and the cut-off rigidity of these stations are listed in Table I.

The data for each station corrected for pressure, are normalized such as the intensities at the solar minimum (October 1976) are taken equal to 1.00 and at the solar maximum (August 1982) are taken equal to zero.

Monthly values of the most important solar flares $N_f \geq 1B$, the relative sunspot number R_z (Zürich Observatory) and the geomagnetic index A_p (Solar Geophysical Data, WDC-A) for the same time period have also been used. The number of high-speed solar-wind streams is taken from the catalogue of Mavromichalaki *et al.* (1988b) which is based on a data compilation by J. King available through the National Space Science Data Center.

Studying correlations between cosmic-ray intensity and a large number of solar, interplanetary and terrestrial parameters we accepted the above parameters as source functions representing these solar activity indices. On the other hand we have studied the time lag of the cosmic-ray intensity in relation to these parameters (Mavromichalaki *et al.*, 1988a). Finally we gave a generalized empirical relation for the cosmic-ray modulation according to which the modulated cosmic-ray intensity is expressed by the formula

$$I = C - 10^{-3}(a_1 R_z + a_2 N_f + a_3 S - a_4 A_p) \qquad (1)$$

Where C is a constant which depends linearly on the cut-off rigidity of each station (Table I). R_z, N_f, S, A_p are the solar-terrestrial parameters incorporating the time-lag (Mavromichalaki *et al.*, 1988a) and a_i $(i = 1, ..., 4)$ are factors which have been calculated using the RMS-minimization method. This method used to find the optimum values for the above mentioned factors, consists of searching for those values which result in the minimum RMS deviation from zero of the difference between the observed and calculated values of C.R. intensity (ΔI) assuming a progressive dependence of the above parameters (R_z, N_f, S, A_p). These factors a_i $(i = 1, ..., 4)$ are respectively, 3.4, 1.2, 3.5, and 0.1. Examining the above relation (1) and applying this to the nine ground based detecting cosmic-rays, we observe that the constant C is linearly correlated to the cut-off rigidity of each station (Table I). The variation of C versus the rigidity of the stations is presented in Figure 1. From this Figure we derive the relation

$$C = 0.95 + 0.005P \qquad (2)$$

where P is the cut-off rigidity of each station.

The linear relationship between the cosmic-ray intensity and the solar terrestrial parameters is established by carrying out a multiple correlation analysis. The multiple correlation coefficient is found to be equal to 0.96 ± 0.01.

The 11-year variation of the observed neutron monitoring data of each station I_{obs} and the corresponding I_{cal} values calculated from equation (1) on monthly basis is shown in Figure 2. The continuous line represents the observed cosmic-ray intensity I_{obs} and the dashed one gives the corresponding I_{cal} values. It is worth mentioning that for all nine neutron monitoring stations the agreement between the measured cosmic-ray intensities and those calculated by equation (1) is very good.

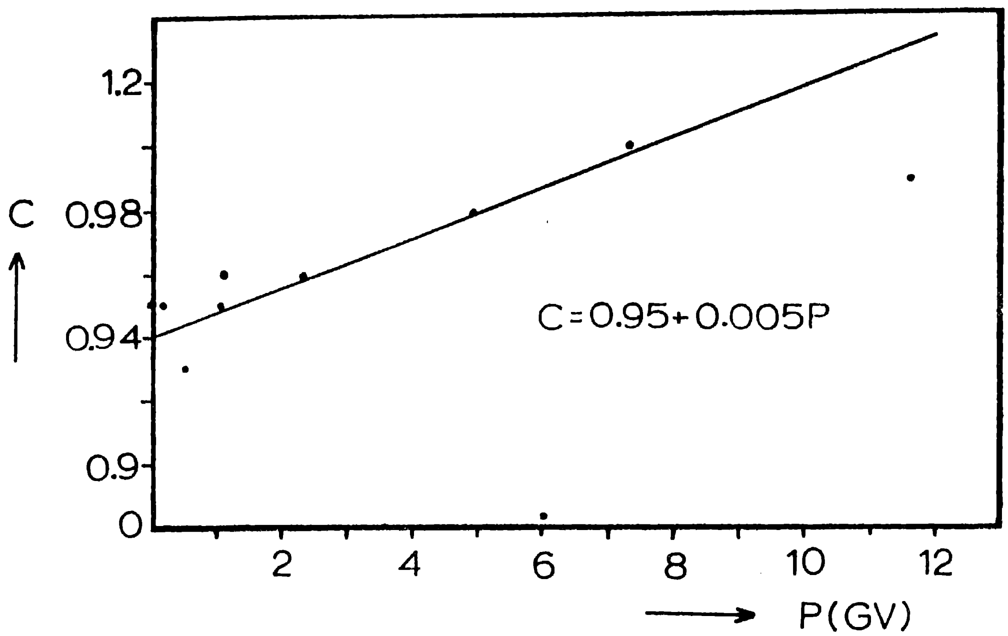

Fig. 1. Rigidity dependence of the constant C for the time interval 1975–1985.

The standard deviation between the observed and calculated values of cosmic-ray intensity on monthly basis is found to be 10–12%. There is an exception for the Tokyo neutron monitor data where the standard deviation gives the value of 15%.

3. Periodic Variations in Cosmic-Ray residuals

Subtracting the values of cosmic-ray intensity, calculated by the equation (1), from the observed ones we estimate the residuals $\Delta(I_{\rm obs} - I_{\rm cal})$ which are shown in Figure 3. Although these values are independent on the 11-year and other variations as was expected, a remarkable short-term variation is present. We therefore made a power spectral analysis of these; data for all stations used here according to the Blackman and Tuckey method (Mitchell, 1966). This analysis is presented for each station separately in Figure 4. The results obtained exhibit a peak at a 97.5% significant level corresponding to a period of about 3.7 months and another one of 2.7 months period at a significant level of 95%. The first periodicity of 3.7 months which is really significant is observed at all stations except for the equatorial station of Tokyo.

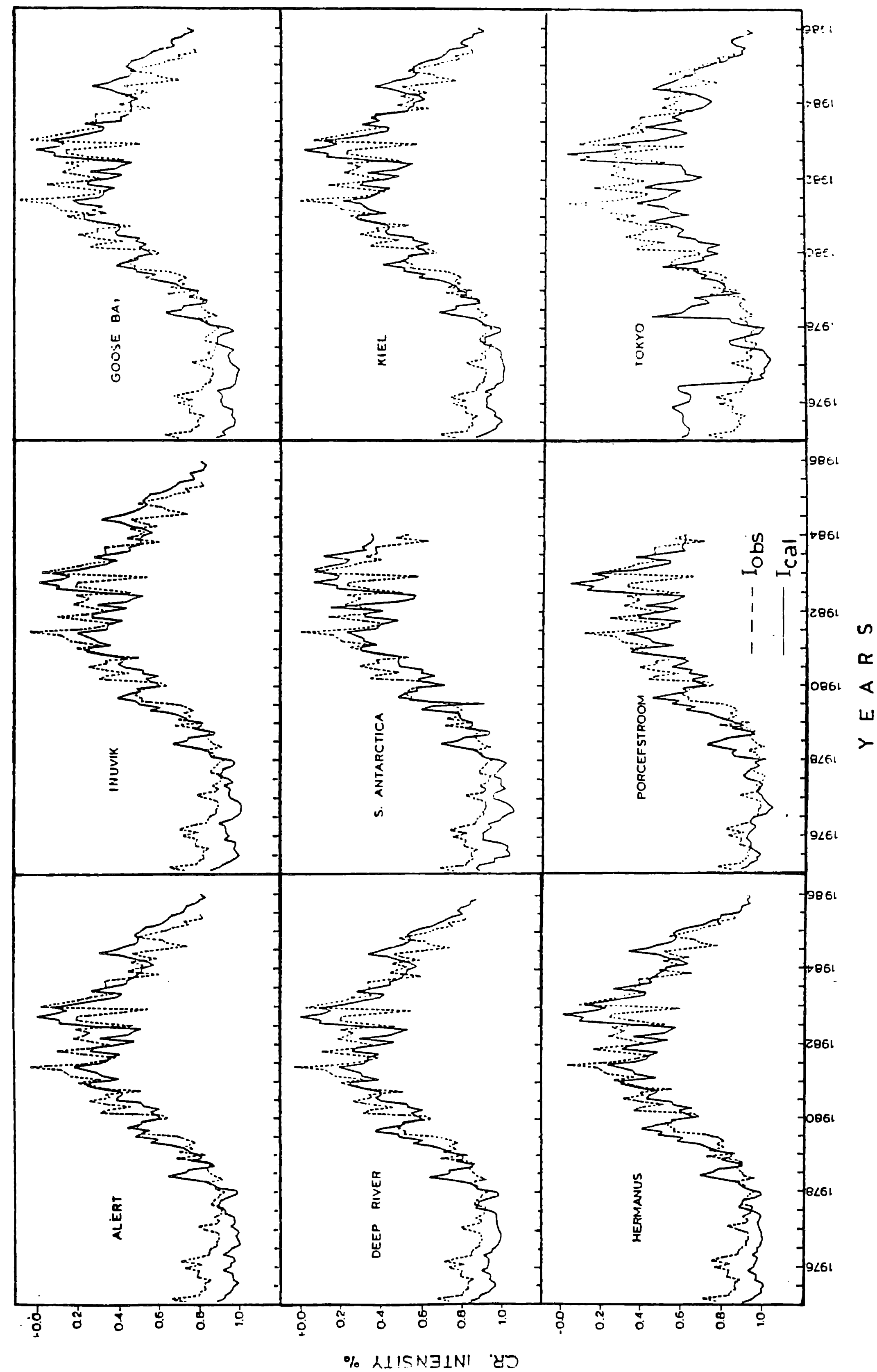

Fig. 2. The 11-year variation of cosmic-ray intensity for the nine NM stations is presented. The continuous line represents the observed cosmic-ray intensity I_{obs} and the dashed line gives the corresponding values I_{cal} calculated by the relation (1).

To our knowledge these peaks of $\approx$ 2.7 and $\approx$ 3.7 months in the cosmic-ray data have not been reported elsewhere and their cause remains at present unknown. It may be of galactic origin which is another important short period of external origin. An effort is made to explain these short-term variations. Regarding the period of 2.7 months we can say that periodicities of 2.8 and 6 months have been found by Mavromichalaki *et al.* (1989) in the geomagnetic K-indices of Athens and Sofia magnetic Observatories for the period 1965–1984. Nevertheless an approximately 3 month recurrency was found for the 557 A ($2p^4\ {}^1D \rightarrow 2p^4\ {}^1S$) in the (OI) airglow intensity as measured by the Maruyama Observatory for the period 1957–1961 (Ward and Silverman, 1962). It seems that the observed approximately 3 month periodicity in the 557 A [OI] of the Maruyama Observatory might be a genuine period which reflects the mean 2.8 months period found in the K-indices and continously in the cosmic-ray residuals. This suggestion is based on the rational of the exciting relationship between geomagnetic activity variations and solar activity. Although any quantitative appreciation of influencing parameter of galactic (exocolar) origin on the variations of cosmic-ray intensity measured in the ground is considered negligible or unknown (e.g. C^{14} atom production galactic cosmic-rays) any possible relationship between periodic phenomena of galactic origin and terrestrial phenomena must not be excluded. In fact, power spectral analysis applied to the light curve of RR Tauri (a young star) exhibited period of 80, 200 and 533 days with some variations in the peak position and power for different decades (Silverman *et al.*, 1971). The spectral type of RR Tauri is Aze and is located in a small nebula at the edge of the Taurus clouds. Thus the 2.7 months period may be of galactic origin which is another important short period of external origin (otherwise periods below 22 years are considered to be of solar origin).

Concerning the period of 3.7 months, astronomers hold that flares show a stochastic distribution, but closer examination discloses cycles of solar flares with mean periods of 9 years, 2.25 yrs and 3.3 months (Ichimoto *et al.*, 1985; Landscheidt, 1984), while other flare cycles in the range of months are related to variation in dT/dt, the impulses of the torque of the Sun's center of mass. Indeed, a strong 100-day cycle is formed by the change in the angular acceleration of the vector of the tidal forces of the planets Venus, Earth and Jupiter that shows a very strong relationship to energetic X-ray bursts $\geq$ XI (Landscheidt, 1984) which presents a torque cycle harmonic of 2.4 months (Landscheidt, 1988). It should be noted that impulses of the torque which drive the Sun's motion around the Center of the mass of the Solar System in the ecliptic plane, relative to the Sun's Center, are the special quantitative criterion of relationships with the secular and supersecular cycles of solar activity. Such impulses of the torque are evidently modulating the radio carbon variations in the atmosphere and so the cosmic-ray intensity in the ground.

A further possible interpretation regarding the genuiness at the 3.7 month period may be that this period is the mean value of the 4.8 month period of the energetic

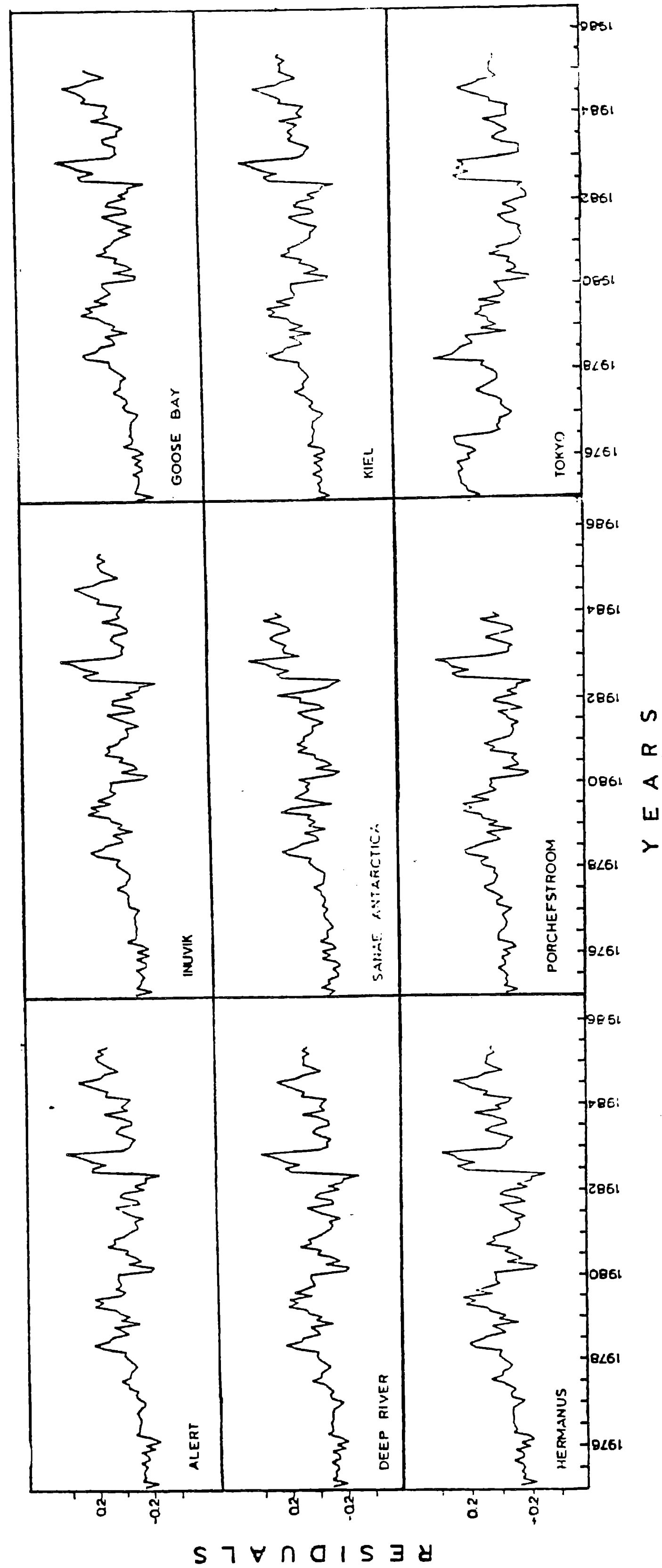

Fig. 3. Differences of the observed cosmic-ray intensities I_{obs} and the I_{cal} values calculated by the relation (2) for each station.

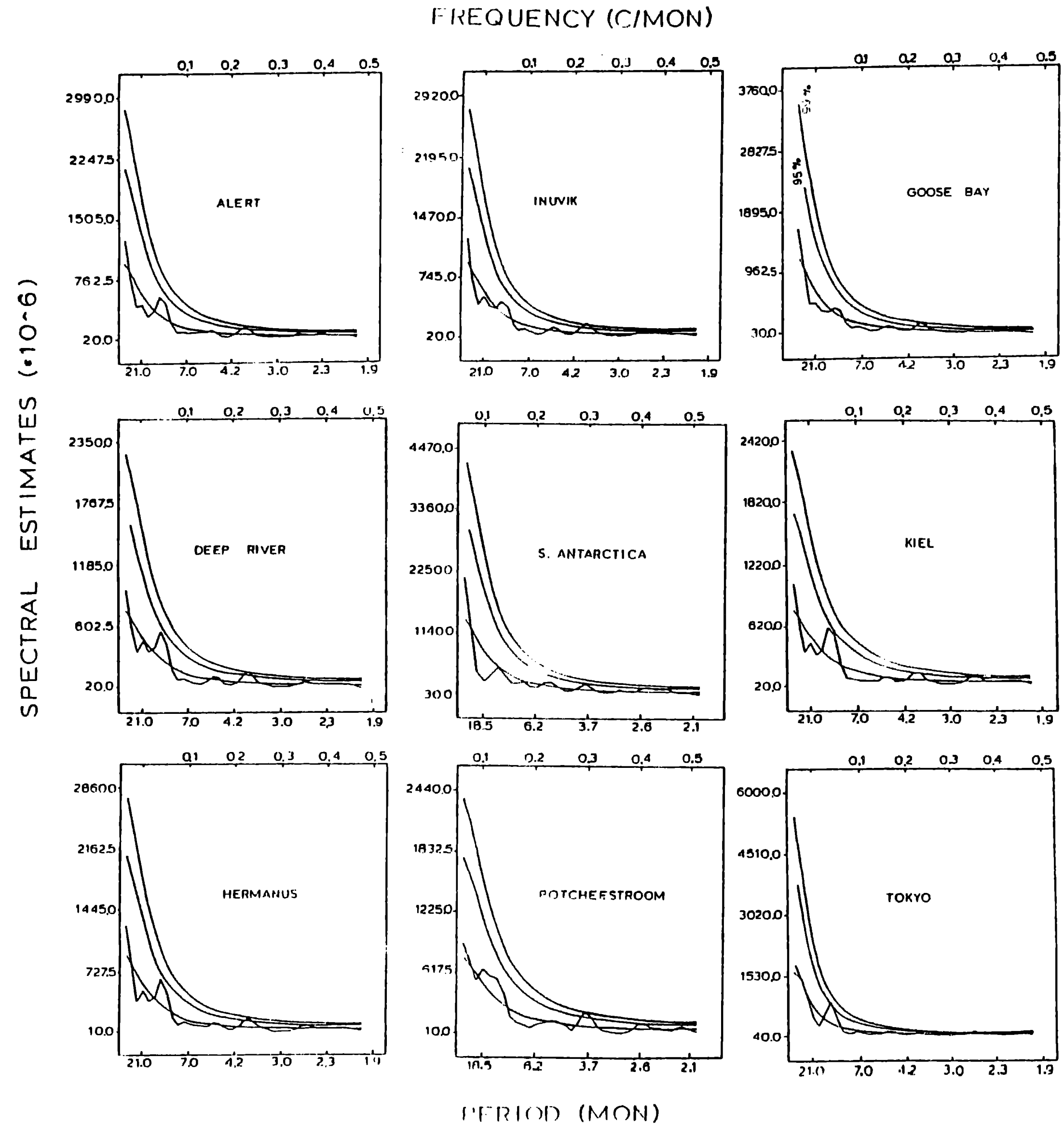

Fig. 4. Blackman-Tuckey power spectrum of the residuals $\Delta(I_{\rm cal} - I_{\rm obs})$ for all stations examined here. The significance of the deviation of the outstanding peaks from the Markov red noise (R) can be evaluated by means of the confidence level curves.

solar eruptions (X-ray bursts $\geq$ XI) obtained by Landscheidt (1988) and the 2.7 month period of galactic origin which gives the 2.8 month period found in the geomagnetic K-indices.

4. Discussion

As it is known, cosmic-ray modulation occurs due to the interaction of galactic cosmic-rays with the plasma streams which are ejected from the Sun and frozen in magnetic fields, carried in the form of regular (large-scale) fields and random magnetic inhomogenities. Particles which come from the Galaxy meet these streams and are swept away by the interplanetary magnetic fields. Hence the intensity of galactic particles inside the heliomagnetosphere turns out to be smaller than in the Galaxy. The modulation efficiently depends upon various factors namely: the magnitude and direction of regular magnetic fields, the level of magnetic disturbances, the solar wind speed, the size and shape of the heliomagnetosphere.

The diffusion-convection and adiabatic decelaration theory (Gleeson and Axford, 1967) of galactic cosmic-rays into a spherically symmetric solar wind would lead to a long-term variation. In the light of this model the modulations are well explained by setting proper physical states in the modulating region, but it is not so clear how these states are related to solar activities. According to this theory several authors (Nagashima and Morishita, 1980; Xanthakis *et al.*, 1981; Mavromichalaki and Petropoulos, 1987) studying previous solar cycles have shown that the cosmic-ray modulation can be described by the following integral equation which is derived from a generalization of Simpson's coasting solar wind model (1963) as:

$$I(t) = I - \int f(r) S(t-r)\, dr \tag{3}$$

Where I and $I(t)$ are, respectively, the galactic (unmodulated) and modulated cosmic-ray intensities, $S(t-r)$ is the source function representing some proper solar activity index at a time $t-r$ $(r \geq 0)$ and $f(r)$ is the characteristic function which expresses the time dependence of solar disturbances represented by $S(t-r)$.

In this work it is pointed out that the modulation of cosmic-rays during the 21st solar cycle can be described on a monthly basis by the source function of the equation (3) which is expressed by the linear combination of four indices: the sunspot number R_z, the solar flares of importance $\geq 1B$ N_f, the high-speed solar-wind streams S and the geomagnetic index A_p. The characteristic function $f(r)$ of all these indices has a constant value during this solar cycle calculated by the RMS-minimization method. In this way the modulated cosmic-ray intensity is equal to galactic cosmic-ray intensity (unmodulated) at a finite distance, corrected by a few appropriate solar, interplanetary and terrestrial activity indices, which cause the disturbances in interplanetary space. This model reproduces to a certain degree the cosmic-ray modulation which will be very useful to cosmic-ray research.

An interesting remark to the diffusion-convection spherically symmetric model from which the above considered relation is obtained is that it does not take into account the effect of non uniform large-scale magnetic fields on the cosmic-ray modulation. Indeed it is known that magnetic fields strongly affect the particle propagation in the following main respects:

i) They make the medium anisotropic producing the difference between the transverse diffusion current and the longitudinal diffusion current and leading to the occurrence of the Hall current.

ii) They cause rather intensive transverse particle drift whose velocity for particles with $T \geq 0.5$ GeV exceeds the convection velocity (Jokipii *et al.*, 1977; Isenberg and Jokipii, 1978; Kota and Jokipii, 1991) so that the drift motion may essentially influence the magnitude and direction of the particle flux anisotropy and anisotropy time-variations and

iii) They may lead to different modulations of electons and protons on the same rigidity (and the same velocity) because the drift velocity in non-uniform magnetic field depends on the sign of particle charge.

The dependence of the drift speed on the sign of particle charge gives rise to the hysteresis phenomenon observed by Moraal *et al.* (1979). Everson *et al.* (1983) come to the conclusion that the modulation process is rather insensitive to the particle charge sign and that the stationary modulation theory such as the one we have used in this work describes quite satisfactorily the modulation processes in large-time scales. An effort was made in the past by Mavromichalaki and Petropoulos (1984) in order to attribute a different modulation process to the cosmic-ray intensity from the coronal-hole streams depending on their interplanetary magnetic field polarity. This process was applied with success to the 20th solar cycle but not to the 21st solar cycle. Recently Nagashima *et al.* (1991) tried to obtain a better correlation of cosmic-ray intensity with solar activity using spherical harmonics of the solar magnetic field, for the period 1976–1985. Kota and Jokipii (1991) have reported that the drift model of cosmic-rays propagation attributes the 11-year variation to changes in the configuration of the heliospheric current sheet.

Finally, the search which was made to explain the periodic variations of the residuals of cosmic-ray intensity will lead us to a better understanding of the relations among coronal structure, interplanetary and galactic structure and cosmic-rays.

5. Conclusions

The modulation character of the cosmic-ray intensity for the 21st solar cycle is described successfully by the analytical method which utilizes the empirical relation (1). According to this method based on the diffusion-convection theory we would reproduce to a certain degree the modulation of cosmic-rays detected at Neutron Monitor Stations with the proper source functions (R_z, N_f, S, A_p) and would also associate these source functions with the electromagnetic properties in the modulating region.

Still remaining short term variations in the residuals of the observed cosmic-ray intensity values from the estimated ones appear 2.7 and 3.7 month periodicities which may be of galactic origin which influence the solar dynamics and may be

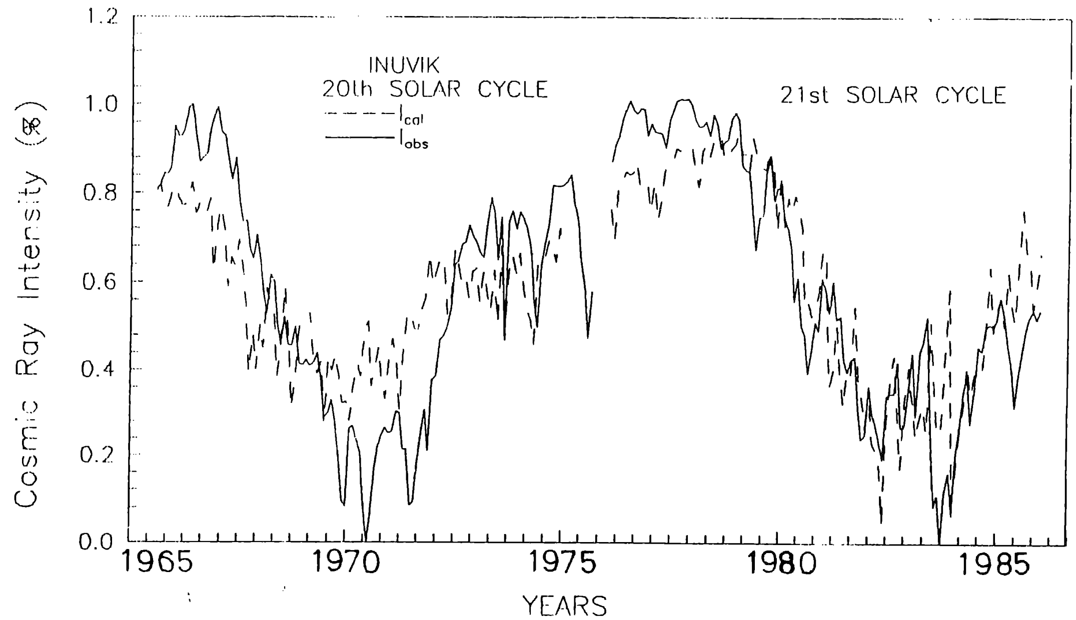

Fig. 5. The 11-year variation of cosmic rays for the typical station of Inuvik for the 20th and 21st solar cycles. It is interesting the good agreement of the observed and calculated values.

another short period of external origin. It means that an effort must be made to improve this proposed model for the cosmic-ray modulation in terms of a new source function of galactic origin.

It is noteworthy that this method has been applied with satisfactory results to three solar cycles (19, 20, 21) with some corrections for each cycle. The results for the 20th and 21st solar cycles for a typical station of Inuvik are shown in Figure 5. Perhaps a correction of this method, using for example, a new source function with non-uniform magnetic fields which strongly affect the particle propagation and/or the transient phenomena which are highly correlated with the cosmic-ray intensity will give a more appropriate description of galactic cosmic-ray intensity.

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