SIMULATION OF LONG-TERM COSMIC-RAY INTENSITY VARIATION

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Abstract. Selecting the most appropriate source functions among the various solar, interplanetary and terrestrial activity indices we have attempted to reproduce to a certain degree the long-term modulation of galactic cosmic-rays. For this study monthly cosmic-ray data from nine world-wide neutron monitor stations for the period 1975–1985 have been analysed. The empirical formula which has been used to compute the long-term cosmic-ray variations follows the observations fairly well.

It is noteworthy that the residuals in the cosmic-ray intensity between that observed and that calculated by this empirical formula exhibits a still remaining short-term variation in all stations of 2.7 and 3.7 months. Possible interpretations of these observed periodicities related to galactic origin are given.

1. Introduction

As is well known the cosmic-ray intensity observed at the Earth and in the Earth and in its vicinity outside the magnetosphere exhibits an approximate 11-year variation anticorrelated with solar activity with perhaps some lag (Forbush, 1958; Pomerantz and Duggal, 1974; Perko and Fisk, 1983, to name a few). A great effort is carried out in order to express this long-term variation of galactic cosmic-ray intensity by appropriate solar indices. Note sunspot number has been used by Nagashima and Morishita (1980), solar flares by Hatton (1980) and geomagnetic index by Chirkov and Kuzmin (1979). Other authors like Xanthakis, Mavromichalaki, and Petropoulos (1981) and Nagashima and Morishita (1980) have taken into account the contribution of more than one solar and/or geophysical parameters to the modulation process. Mavromichalaki and Petropoulos (1984) found a relation between the modulated cosmic-ray intensity during the 20th solar cycle, and a combination of the relative sunspot number, the number of proton events and the geomagnetic index A_p. In a later work, Mavromichalaki and Petropoulos (1987) improved this empirical relation by including the number of corotating solar wind streams. 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 this paper we attempt to reproduce the long-term cosmic-ray modulation for the 21st solar cycle taking into account the influence of the number of sunspots, solar flares ($\geq$ 1B), solar wind streams and the geomagnetic index A_p. We have reproduced the monthly cosmic-ray intensity using the above mentioned parameters, entering in all of them the effect of time-lag. In this way we can say that the effect of Forbush decreases has been inserted indirectly in the cosmic-ray study in that the chosen solar parameters

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are connected with solar events which in the first instance cause the Forbush decreases and the magnetic disturbances.

2. Data Analysis

In order the study the long-term modulation in cycle 21 cosmic-ray intensity data have been used from nine world-wide neutron monitor stations (super NM-64) covering a wide range of cut-off rigidities from 0.00 to 11.61 GV (Alert, Inuvik, Goose Bay, Deep River, Sanae Antarctica, Kiel, Hermanus, Potchefstroom and Tokyo). The pressure-corrected data for each station were normalized with the intensity taken equal to 1.00 at solar minimum (October 1976) and equal to 0.00 at solar maximum (August 1982). In this study we have used the number of solar flares of importance ≥ 1B (N_f), in each month, the relative sunspot number (Rz; Zürich Observatory), the geomagnetic index A_p (*Solar Geophysical Data*) and the high-speed solar wind streams (Mavromichalaki, Vassilaki, and Marmatsouri, 1988).

A detailed study of all these data has led us to a generalized empirical relation connecting the monthly mean modulated cosmic-ray intensity with the difference between a constant C and the sum of the most important solar and terrestrial indices which affect the cosmic-ray modulation. The empirical relation is given by

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

where the constant C depends linearly on the cut-off rigitity for each station; R_z, N_f, S, A_p are the solar-terrestrial parameters incorporating the time-lag (Mavromichalaki *et al.*, 1988) and a_i ($i = 1$ to 4) are the factors calculated using the RMS-minimization. These are, respectively, 3.4, 1.2, 3.5, and 0.1.

Applying relation (1) to the nine cosmic-ray stations we find that the constant C is linearly correlated to the cut-off rigidity of each station. The variation of C versus the

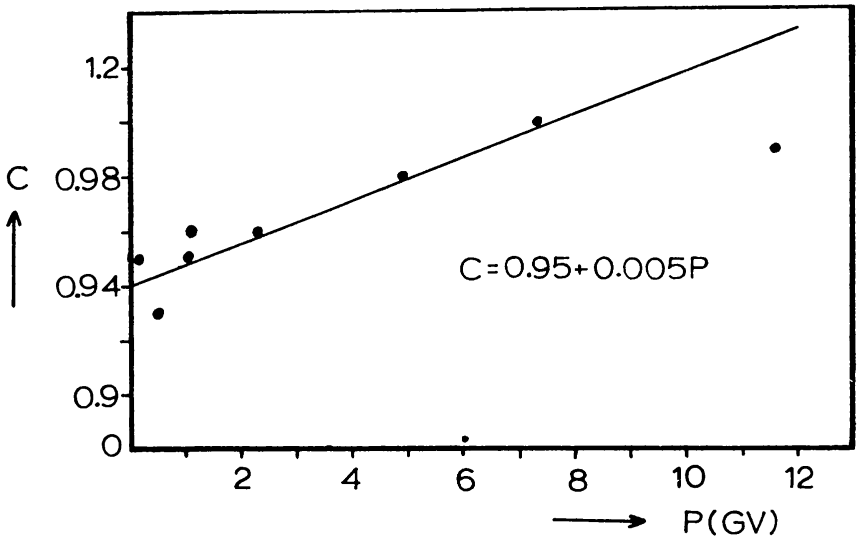

Fig. 1. Rigidity dependence of the constant C for the time interval 1975–1985.

rigidity is shown in Figure 1; from this we get

$$C = 0.95 + 0.005P\,, \tag{2}$$

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

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

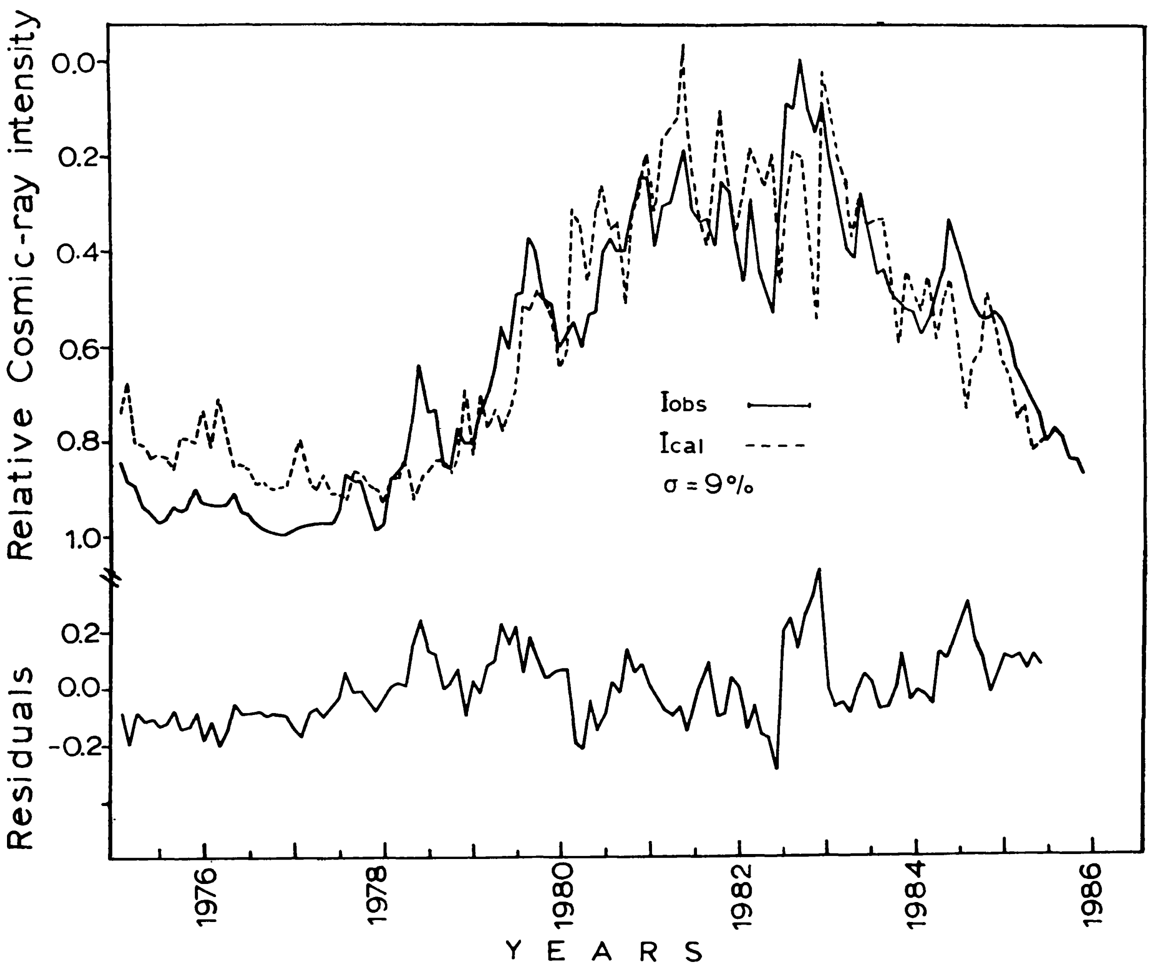

Fig. 2. The 11-year variation of cosmic-ray intensity for an average station is presented. The continuous line represents the observed cosmic-ray intensity O_{obs} and the dashed line gives the corresponding value I_{cal} calculated by the relation (1) (*top panel*). The lower panel gives the differences between the observed and the calculated values.

The 11-year variation of the observed monthly cosmic-ray values, I_{obs} and the corresponding calculated values from the relation (1), I_{cal} averaged for the nine stations is given in the upper panel of Figure 2. The lower panel indicates the residuals between the two. The standard deviation is 9% which suggests a very good approximation.

3. Periodicities in Cosmic-Ray Data of 2.7 and 3.7 Months

Examining carefully the residuals $\Delta(I_{\text{obs}} - I_{\text{cal}})$ in Figure 2 we have noticed that although they are independent of the 11-year variation, they exhibit a remarkable short-term variation. A spectral analysis of these data points using the Blackman and Tukey method (Mitchell, 1966) shows a peak at 99% significant level corresponding to a period of about 3.7 months and another one of about 7 months period at 95% significant level (Figure 3); these have not been reported elsewhere to our knowledge and the cause for these periodicities remains unknown.

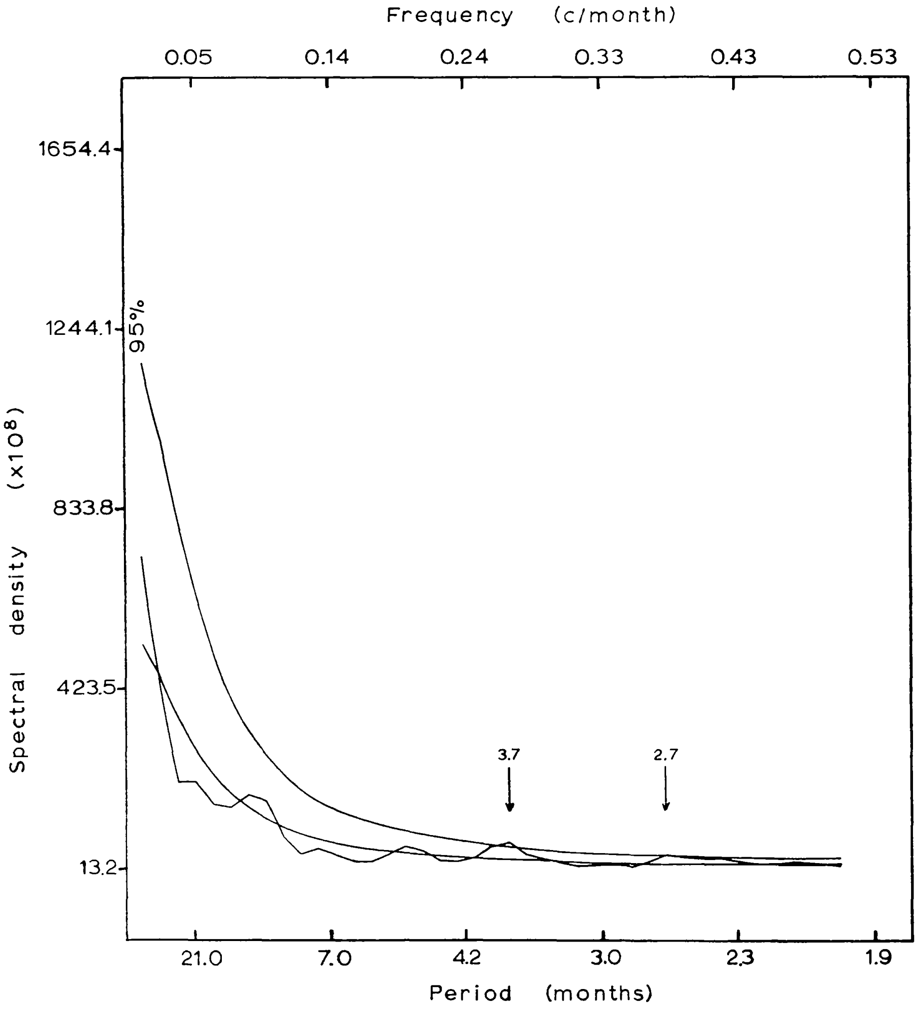

Fig. 3. A Blackman–Tukey power spectrum of the residuals $\Delta(I_{\text{obs}} - I_{\text{cal}})$ for an average station is given. The significant level of 95 is also shown.

Attempting to explain these short-term variations we have noticed that periodicities of 2.8 and 6 months have recently been found by Mavromichalaki, Belehaki, and Liritzis (1989) in the geomagnetic *K*-indices from the Athens and Sofia magnetic observatories over the interval 1965–1984 and an approx. 3-months recurrency in the 5577 Å ($2p^4\,{}^1D - > 2p^4\,{}^1S$) [O I] airglow intensity as measured by Maruyama

Observatory over the interval 1957–1961 (Ward and Silverman, 1962). 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 exhibited periods of 80, 200 and 533 days with some variations in the peak position and power for different decades (Silverman, Ward, and Shapiro, 1971).

Astronomers find that flares show a stochastic distribution, but on closer examination find mean periods of 9 yr, 2.25 yr and 3.3 months (Ichimoto *et al.*, 1985; Landscheidt, 1984), Flare cycles with periods of months are observed to be related to variations in $\mathrm{d}T/\mathrm{d}t$, 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 show a very strong relationship to energetic X-ray bursts $\geq$ X1 (Landscheidt, 1984) which presents a torque cycle harmonic of 2.4-months (Landscheidt, 1988). It should be noted that impulses of the torque modulate the radio carbon variations in the atmosphere and thus the cosmic-ray intensity on the ground.

Another possibility is that the 3.7-months period may be the mean of the 4.8-month period of the energetic solar eruptions (X-ray bursts $\geq$ X1) obtained by Landscheidt (1988) and the 2.7-month period of galactic origin which gives the 2.8 months period found in the geomagnetic K-indices.

4. Discussion

The cosmic-ray modulation 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.

We have invoked the relation

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

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 the modulation of cosmic-ray intensity is described on a montly basis empirically by the source function of Equation (3) which is an arbitrary linear combination of the four indices: the sunspot number R_z, the solar flares of importance $\geq$ 1B, N_f, the number of 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. By 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 and thus modulate the C. R. intensity.

Lockwood and Webber (1987) have shown that the 11-year cosmic-ray intensity variation can be simulated by the cumulative effects of the observed Forbush decreases while we use the solar flares of importance ≥ 1B and the high speed solar wind streams, which are associated with the Forbush decreases and magnetic disturbances. Note that near solar minimum there are no Forbush decreases observed.

Finally, an attempt is made to explain the periodic variations of the residuals of cosmic-ray intensity.

5. Conclusions

The long-term modulation of the cosmic-ray intensity for the 21st solar cycle is generated empirically by an analytical method which utilizes the empirical relation (1). It reproduces to a certain degree the modulation of cosmic-rays with a linear combination of the source functions (R_z, N_F, S, A_p) which are associated with the electromagnetic properties in the modulating region. We hypothezised that the 2.7 and 3.7-month periodicities in the residuals of the observed cosmic-ray intensity values from that computed by Equation (1) may be of galactic origin. We have referred to similar periodicities in other phenomena. An effort will be made in the future in order to refine our proposed model for the cosmic-ray modulation in terms of a new source function of galactic origin.

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