TIME-LAG OF COSMIC-RAY INTENSITY

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Abstract. The best correlation coefficient between the monthly cosmic-ray intensity of the Inuvik Station and various kinds of solar, interplanetary, and geophysical parameters has been found. It is calculated for different time-lags of cosmic-ray intensity with respect to these parameters. The maximum of these coefficients lead us to a useful empirical model for the 11-year cosmic-ray modulation.

1. Introduction

A number of studies have shown that the long-term variations of galactic cosmic-ray intensity can be expressed by appropriate solar and terrestrial indices (Forbush, 1958; Rao, 1972; Pomerantz and Duggal, 1974; Moraal, 1976; Morfill *et al.*, 1976). For example, Nagashima and Morishita (1980a) have used the sunspot number in order to simulate the cosmic-ray intensity from the solar activity.

Hatton (1980) pointed out that the eleven-year cosmic-ray intensity variation is related more to the occurrence of solar flares than to the presence of sunspots. The geomagnetic index has been used by Balasubrahmanyan (1969), Chirkov and Kuzmin (1979) in order to study the cosmic-ray intensity variations. Other authors (Xanthakis *et al.*, 1981; Nagashima and Morishita, 1980a) have taken into account the contribution of more than one solar and geophysical parameter, to the cosmic-ray modulation process such as solar flares, proton events, etc.

Except for these parameters, in order to understand the cosmic-ray modulation it is very useful to determine the structure of the interplanetary medium and its influence on cosmic-ray intensity variations. An attempted correlation of the long-term variation in cosmic-ray intensity with the solar wind speed and interplanetary magnetic field (IMF) magnitude has run into difficulty (Mathews *et al.*, 1971; Yoshimura, 1977). However, Barichello (1978) has pointed out that there is a significant negative correlation between the cosmic-ray intensity and solar wind speed over short periods of a few solar rotations. Recent studies of Iucci *et al.* (1979) reveal that this correlation is improved for periods of high-speed solar wind streams (Duggal, 1977). This led the above authors to distinguish two types of effects on cosmic-ray intensity due to high-speed solar wind streams which originate from two different solar sources, such as coronal holes and solar flares (Dryer, 1974; Burlaga, 1979). Venkatesan *et al.* (1982) have suggested that events of the years 1973–1976 are essentially due to high-speed streams associated with

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coronal holes and events of the interval 1977–1978 are due to fast streams from solar active regions with flare activity. For all these reasons we have studied in this work the possible influence of the interplanetary indices and especially of the solar-wind streams on the cosmic-ray intensity during the 20th solar cycle.

This study has been done taking into account the well-known hysteresis effect of the cosmic-ray intensity following different solar, interplanetary, and terrestrial parameters. Forbush (1958) has shown that the cosmic-ray intensity recorded by ion chambers lagged behind the sunspot numbers by 6 to 12 months during solar cycles 17 and 18. Simpson (1963) interpreted this lag as the result of changing conditions within a modulating region, the size of which could be estimated by multiplying the time lag by the average solar wind velocity. Hatton (1980) and Hatton and Bowe (1981) extended this idea and suggested that the modulation of the cosmic-ray intensity during solar cycle No. 20, was primarily due to the effect of solar flare-generated disturbances, travelling outward to the boundary of the modulating region. We have found the best correlation coefficient between the monthly cosmic-ray intensity and the sunspot number, as well as other indices – i.e., the proton events, the solar flares, the geomagnetic index and the fast solar wind streams for different time-lags. The time-lag which corresponds to the cross-correlation coefficient of each above-mentioned parameter led us to an interesting relation of the cosmic-ray intensity with its most suitable source functions.

2. Selection of Data

In order to study the long-term modulation of cosmic-ray intensity for solar cycle 20, data of cosmic-ray intensity from the Inuvik neutron monitoring station (Super NM-64, threshold rigidity 0.18 GV) have been used extending over the period 1964–1975. The pressure corrected monthly intensity values were normalized by

$$\frac{I_i - I_{\min}}{I_{\max} - I_{\min}}, \tag{1}$$

where $I_{\min}$ and $I_{\max}$ are, respectively, the minimum and maximum cosmic-ray intensities during the 20th solar cycle and I_i is the corresponding monthly value. Thus, the intensities at solar minimum (May, 1965) are taken equal to 1.00 and those at solar maximum (June, 1969) equal to zero.

For this analysis we have also used the monthly number of flares of importance ≥ 1, the relative sunspot number (Zürich Observatory) and the geomagnetic index A_p for the period 1964–1974 (Solar Geophysical Data). The number of high-speed solar-wind streams (HSPS) is taken from the catalogue of Lindblad and Lundstedt (1981). This catalogue is based on a data compilation by J. King available through the National Space Science Data Center (King, 1977).

According to Lindblad and Lundstedt (1981) for a possible HSPS the difference between the 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}. As various definitions of the

HSPS have been given we believe that this definition is more adequate for the purpose of solar-terrestrial studies because it emphasizes the velocity gradient of a high-velocity stream rather than the maximum velocity.

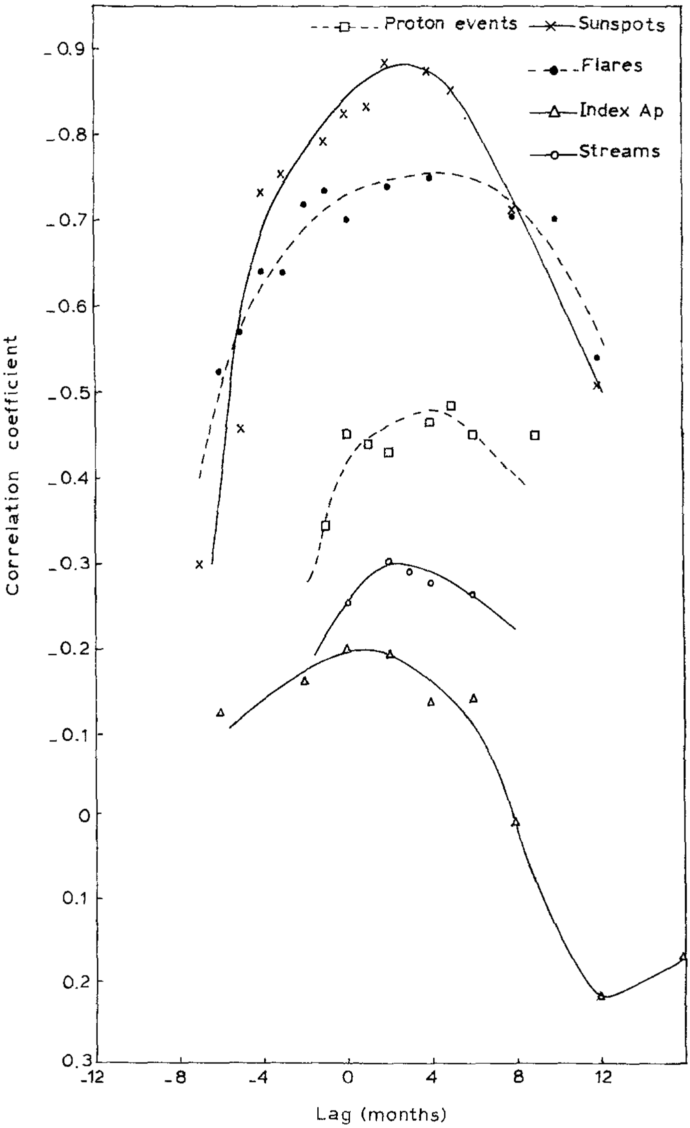

Fig. 1. Correlation coefficient between the monthly cosmic-ray intensity and sunspot number, solar flares of importance ≥ 1, proton events, index A_p and high-speed streams as a function of cosmic-ray intensity lag with respect to these indices for the solar cycle 20.

Recent studies of Iucci *et al.* (1979), Venkatesan *et al.* (1982) have shown that the high-speed solar-wind streams are of two basic types: the first one is a long lasting HSPS emitted by coronal holes and the second one, characterized by lower solar wind speed, seems to be associated with strong active regions emitting solar flares and producing Forbush decreases in the Earth. Remarkable differences have been found between the interplanetary parameters characterizing the streams of these two different regions.

3. Hysteresis Effect

It is known that the time-lag between cosmic-ray intensity and solar activity varies from several to 12 months depending on the solar cycle and the activity index adopted (Dorman *et al.*, 1977; Nagashima and Morishita, 1980a). Simpson (1963) attributed this time-lag to the dynamics of the build-up and subsequent delayed relaxation of the modulating region.

A correlation analysis between the monthly mean cosmic-ray intensity and the monthly solar activity (sunspot number and solar flares of importance ≥ 1) as a function of the lag of the cosmic-ray intensity with respect to solar activity is shown in Figure 1 for the solar cycle 20. We can see that the cross correlation coefficient for the sunspot number is at a maximum for a time-lag of 2 months and for the solar flares of importance ≥ 1 for a time-lag of 4 months. Hatton (1980) has given the same results for the Leeds cosmic-ray station for the same time period. (The Leeds neutron monitor has a threshold rigidity of 2.20 GV and is a typical high-latitude sea-level station.)

It is remarkable that the above time-lags between cosmic-ray intensity and solar activity (as indicated by sunspot number and solar flares) for the solar cycle 20 are shorter than those of the previous cycle (Pomerantz and Duggal, 1974), because the solar activity was less during solar cycle 20 than previously. It confirms the fact that the dimensions of the heliosphere are not constant but depend upon the level of activity during a given solar cycle, that is, the heliosphere has a larger size during the more active cycles.

Since periods of higher than average solar-wind velocity are followed by decreases in the cosmic-ray intensity, a correlation analysis between the monthly cosmic-ray intensity and the monthly number of high-speed solar-wind streams is carried out. The correlation coefficient is maximum when a lag of three months is introduced into the streams data (Figure 1). This is consistent with the Hatton's (1980) result that the time-lag between cosmic-ray residuals (observed and simulated by solar flare data) and solar-wind velocity is three months. This relatively short lag may indicate that the influence of fast streams on cosmic-rays is limited to smaller regions around the Sun.

The same correlation analysis has been carried out between monthly cosmic-ray intensity and geomagnetic index A_p. It is found that there is no time-lag of cosmic-ray intensity recorded at the Earth with respect to the geomagnetic activity. Using neutron monitor data for the solar cycle 19, Balasubrahmanyan *et al.* (1967) showed also that

TABLE I

Cross correlation coefficient and the corresponding time-lags for the solar cycle 20

Indices	r	Lag (months)
Sunspot number	−0.88	2
Solar flares ≥ 1	−0.76	4
Proton events	−0.48	4
Streams	−0.30	3
Index A_p	−0.20 / +0.33	0 / 12

Bartels' A_p index correlates with the cosmic-ray intensity without pronounced phase lags. It is interesting to note that a positive correlation of the cosmic-ray intensity with the index A_p appeared after one year.

The best correlation coefficient and the corresponding time-lag of each above-mentioned index for the solar cycle 20 is given in Table I. It is noteworthy that the time-lag between cosmic-rays and solar, interplanetary, and terrestrial parameters is not significant in this cycle. The hysteresis effect appears to have been considerably reduced.

Furthermore, we computed the correlation coefficient of the cosmic-ray intensity with the number of sunspots, the number of flares ≥ 1 and the number of solar-wind streams for every one year of solar cycle No. 20. It is interesting that the correlation curve for every parameter follows separately the 11-year variation of the solar cycle with a small exception in the case of the sunspot number, as is shown in Figure 2. It is consistent

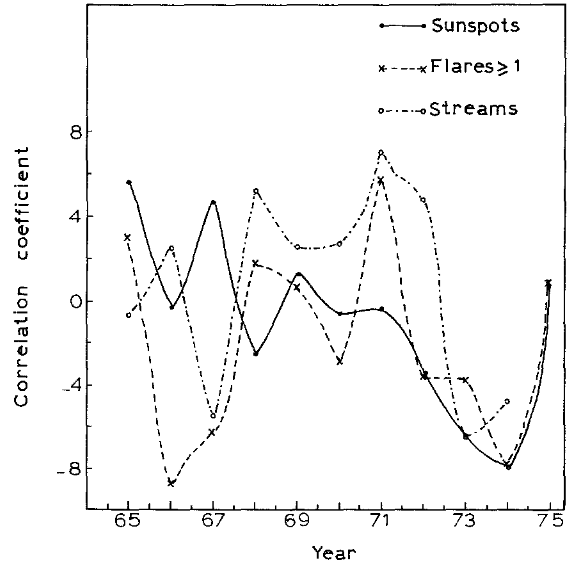

Fig. 2. Correlation coefficient of the cosmic-ray intensity with the sunspot number, the flares ≥ 1 and the number of fast streams for every one year of solar cycle No. 20.

with the evidence that this correlation is stronger (negative) during the solar minima than the solar maxima (Simpson, 1963).

If we compute the correlation coefficient between the cosmic-ray intensity and the geomagnetic index A_p on a yearly basis, it seems that the index A_p has the same behaviour as the other indices but is not so reinforced, as presented in Figure 3. Moreover, it was found from this analysis that the time-lag is shorter in the decreasing phase of solar activity than in the increasing phase, as Simpson (1963) has also shown.

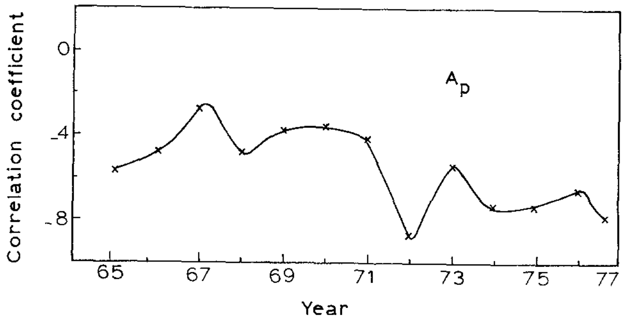

Fig. 3. Correlation-coefficient between the cosmic-ray intensity and the geomagnetic index A_p on a yearly basis.

Generally, we can observe from Figures 2 and 3 that there is a significant variation of the correlation coefficient of the cosmic-ray intensity with every one of the indices, R, N_F, and A_p in the time interval where the solar magnetic field is reversed. As is known, the polarity reversal of the magnetic field due to the 22-year variation took place in mid-1969 in the southern hemisphere of the Sun and ended in August, 1971 when the northern hemisphere completed its reversal (Howard, 1974). Many authors, such as Jokipii *et al.* (1977, 1979), Shea and Smart (1981), Ahluwalia (1981), etc., have also suggested that the modulation of the galactic cosmic-ray intensity has a significant component controlled by the state of the interplanetary magnetic field as transported outward from the Sun and, hence, there is a solar cycle effect on the drift of cosmic-rays in the heliosphere.

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 modulating region, (2) the variations of the mean sunspot heliolatitude from high to low latitudes throughout the 11-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). According to other researchers (Charakhchyan *et al.*, 1977; Ashirof *et al.*, 1977; Nagashima and Morishita, 1980b) the modulation of cosmic-ray intensity is the result of the superposition of the 22-year and 11-year modulation. All these reasons explain the fact that the hysteresis effect has been reduced in this solar cycle which is characterized as a non-active cycle.

4. Solar Wind Streams Effect Upon Cosmic-Ray Intensity

If one examines the cosmic-ray data during the years 1964–1975, several decreases are observed particularly those in 1973 and 1974, which cannot be explained by the solar flare data. During these periods the average solar-wind speed was abnormally high due to the presence of corotating high-speed streams (Hatton and Bowe, 1981). Since interplanetary shocks are also produced by fast streams at the interface between them and the slower moving ambient plasma (Hundhausen, 1979), it would be expected that they too would produce cosmic-ray modulation. It is also established (Zirker, 1977) that fast solar wind streams emanating from coronal holes generate recurrent magnetic storms which occur predominantly at the end of solar cycles. Bowe and Hatton (1982) have suggested that these streams also determine the cosmic-ray intensity at solar minimum. Moreover, because their number and persistence may vary from one minimum to another, the cosmic-ray intensity may also vary.

In our previous work, Xanthakis *et al.* (1981) attempted to find more suitable source functions of cosmic-ray intensity I for various kinds of activity and gave the following empirical relation

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

where C is a constant depending linearly on cut-off rigidity of each station and k is a coefficient which is also rigidity-dependent and related to the diffusion coefficient of cosmic-rays and its transition in space. In this relation we suggested that the major contribution to solar modulation during solar cycle 20 may be attributed to sunspot numbers, to solar flare generated disturbances and to the geomagnetic index A_p.

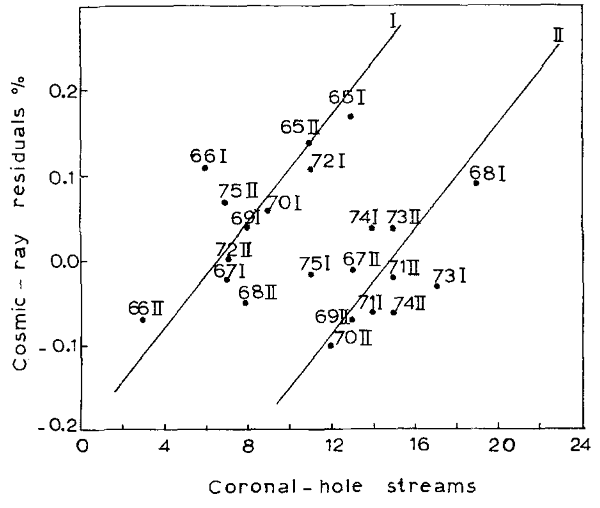

Fig. 4. Correlation diagram between cosmic-ray residuals and coronal-hole streams from 1964 I to 1975 II on a semi-annual basis.

In this work we compared the cosmic-ray residuals (observed and simulated by the sunspot number, the proton events and the index A_p according to Equation (2)) with the solar-wind speed (Feldman *et al.*, 1979) and the number of fast solar-wind streams. These were also compared with the number of the two types high-speed solar-wind streams: emitted by coronal holes and by active regions (Lindblad and Lundstedt, 1981). From all these parameters it is observed that there is a good agreement between the cosmic-ray residuals and the coronal-hole streams especially at solar minimum, as is shown in Figure 4. It gives evidence to a secondary modulation process of cosmic-ray intensity associated with the existence of coronal-hole streams. As mentioned above these streams are characterized by greater solar-wind speed than the streams of the active regions and are observed at solar minimum in the absence of solar-flares.

A correlation diagram between the cosmic-ray residuals ΔI for the Inuvik station on a semi-annual basis and the number of coronal-hole streams is shown in Figure 5. The analytical expression between them is

$$\Delta I = 10^{-3}(3S - a), \tag{3}$$

where $a = 20$ for the line I in Figure 5 and $a = 45$ for the line II in Figure 5. It is

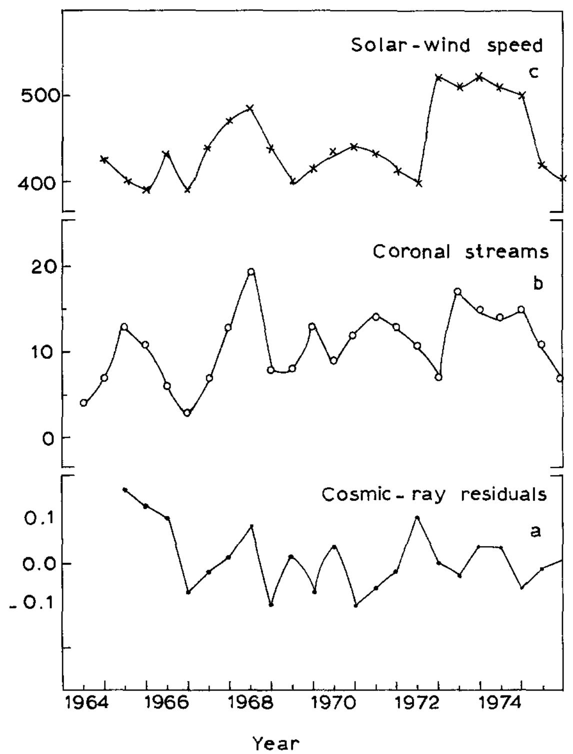

Fig. 5. Solar-wind speed, coronal-hole streams, and cosmic-ray residuals (relation (2)) for the time period 1964–1965.

noteworthy that these lines can be related to the interplanetary magnetic field polarity which appear in each stream. The first one corresponds to the positive polarity and the second one to the negative polarity of the interplanetary magnetic field. This is attributed to a different modulation process to the cosmic-ray intensity from the coronal-hole streams depending on their polarity.

All these observations lead us to a new improved relation for the long-term modulation of cosmic-rays taking into account the presence of the coronal-hole streams. According to this the modulated cosmic-ray intensity that is measured by the ground-based station of Inuvik is equal to the galactic cosmic-ray intensity (unmodulated) at a finite distance corrected by the indices R, N_p, A_p, and S which cause the disturbances in interplanetary space. Equation (1) then becomes

$$I = C - 10^{-3}(kR + 4N_p + 12A_p + 3S - a)\,, \tag{4}$$

where $C = 0.94$, $k = 2$, and $a = 20$ for the values of positive polarity of IMF and $a = 45$ for the negative polarity of it for the Inuvik station. The standard deviation between observed and with relation (4) calculated values for cosmic-rays is $\pm 3.8\%$, while the standard deviation using relation (2) was $\pm 7.6\%$.

This empirical model can be very useful for the calculation of cosmic-ray intensity in a given station. The greatest advantage of this model is that the coefficient of each parameter of relation (4) happens to be the same with the above-calculated time-lag of cosmic-ray intensity with respect to these indices (Table I).

5. Discussion and Results

Several authors (Nagashima and Morishita, 1980a, b; Xanthakis *et al.*, 1981) have shown that the modulation of cosmic-rays can be described by the following integral equation which is derived by a generalization of Simpson's (1963) coasting solar wind model:

$$I(t) = I_\infty - \int f(\tau)S(t - \tau)\,\mathrm{d}\tau\,, \tag{5}$$

where I_∞ and $I(t)$ are, respectively, the galactic and modulated cosmic-ray intensities, $S(t - \tau)$ is the source function representing some proper solar activity index at a time $t - \tau (\tau \geq 0)$ and $f(\tau)$ is the characteristic function which expresses the time dependence of an efficiency depression due to solar disturbances represented by $S(t - \tau)$. Xanthakis *et al.* (1981) have pointed out that the modulations during solar cycle 20 can be described by the source function which is expressed by the linear combination of three indices: the sunspot number R, the proton events N_p, and the index A_p.

In this work it was shown that the cosmic-ray intensity is also controlled by the solar-wind streams and especially the high-speed streams which are emanating from coronal-holes. Therefore, we can write

$$f(\tau)S(t - \tau) = f_R(\tau)R(t - \tau) + f_N(\tau)N_p(t - \tau) + f_A(\tau)A_p(t - \tau) + \\ + f_S(\tau)S(t - \tau)\,. \tag{6}$$

The time-lag τ between the cosmic-ray intensity and each of the above indices can be neglected in relation (6), because it is shorter than six months. We remember that in our analysis we have used semi-annual values. Substituting Equation (6) into the general Equation (5) and identifying with the empirical relation (4) we derive, for the Inuvik cosmic-ray station,

$$I_\infty = C + 10^{-3}\alpha\,, \tag{7}$$

$$\int_0^\infty f_R(\tau)\,\mathrm{d}\tau = 2\times 10^{-3}\,, \tag{8}$$

$$\int_0^\infty f_N(\tau)\,\mathrm{d}\tau = 4\times 10^{-3}\,, \tag{9}$$

$$\int_0^\infty f_A(\tau)\,\mathrm{d}\tau = 12\times 10^{-3}\,, \tag{10}$$

$$\int_0^\infty f_S(\tau)\,\mathrm{d}\tau = 3\times 10^{-3}\,. \tag{11}$$

It is interesting to note that the characteristic function $f(\tau)$ of each index R, N_p, and S has a value which is equal to the time-lag of cosmic-ray intensity with respect to this index. These values can be explained if we choose a simple form for $f(\tau)$: $f(\tau) = 1$ for $0 \le \tau \le T$ and $f(\tau) = 0$ for $\tau < 0$ and $\tau > T$, i.e., the effectiveness of the disturbance in modulating cosmic-rays is independent of distance out to the radius of the heliosphere, if we take $T = 10$ months which is the time taken for the resulting disturbances in the interplanetary medium to propagate to the boundary of the heliosphere (60–70 AU) (Hatton, 1980). It is obvious that a more complicated function for the index A_p is needed.

In concluding, we can say that the small time-lag between cosmic-ray intensity and solar activity as well as between cosmic-ray intensity and interplanetary activity during solar cycle 20 confirms the fact that the solar activity of this cycle was less than previously. It means that the dimensions of the heliosphere are not constant during a given solar cycle. As the contribution of solar wind streams to the modulation process of the cosmic-ray intensity has been confirmed by other studies, the coronal-hole high-speed streams in average improve this contribution, depending on the polarity of the IMF of each high-speed stream. At any rate, this modulation for the solar cycle 20 was of secondary importance to that associated with sunspot number and solar flares.

According to the new model proposed in this work the time-lag of cosmic-ray intensity with respect the more suitable source functions can be used in order to reproduce to a certain degree the modulation and also to associate these functions with the electromagnetic properties in the modulating region. A further study of this model and its extension to other neutron monitor stations will lead us to a better understanding of the relations among coronal structure, interplanetary structure, and cosmic rays.

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References

Ahluwalia, H. S.: 1981, *Adv. Space Res.* **1**, 151.
Ashirof, R. R., Kolomeets, E. V., and Zusmanovich, A. G.: 1977, *Proc. 15th Int. Conf. Cosmic Rays* **3**, 164.
Balasubrahmanyan, V. K.: 1969, *Solar Phys.* **7**, 39.
Balasubrahmanyan, V. K., Boldt, E., and Palmeira, R. A. R.: 1967, *J. Geophys. Res.* **72**, 27.
Barichello, J. C.: 1978, *Solar-Terrestrial Relations*, M.Sc. Thesis, Univ. of Calgary, Canada.
Bowe, G. A. and Hatton, C. J.: 1982, *Solar Phys.* **80**, 350.
Burlaga, L. F.: 1979, *Space Sci. Rev.* **23**, 201.
Charakhchyan, A. N., Bazilevskaya, G. A., Stozhkov, Yu. I., and Charakhchyan, T. N.: 1977, *Proc. 15th Conf. Cosmic Rays* **3**, 200.
Chirkov, N. P. and Kuzmin, A. I.: 1979, *Proc. 16th Int. Conf. Cosmic Rays* **4**, 360.
Dorman, L. I. and Soliman, M. A.: 1979, *Proc. 16th Int. Conf. Cosmic Rays* **4**, 373.
Dorman, L. I., Pimenov, I. A., and Churunova, L. F.: 1977, *Proc. 15th Int. Conf. Cosmic Rays* **3**, 268.
Dryer, M.: 1974, *Space Sci. Rev.* **15**, 403.
Duggal, S. P.: 1977, *Proc. 15th Int. Conf. Cosmic Rays* **10**, 430.
Feldman, W. C., Asbridge, J. R., Bame, S. J., and Gosling, J. T.: 1979, *J. Geophys. Res.* **84**, 7371.
Forbush, S. E.: 1958, *J. Geophys. Res.* **63**, 651.
Hatton, C. J.: 1980, *Solar Phys.* **66**, 159.
Hatton, C. J. and Bowe, G. A.: 1981, *Proc. 17th Int. Conf. Cosmic Rays* **4**, 255.
Howard, R.: 1974, *Solar Phys.* **38**, 283.
Hundhausen, A. J.: 1979, *Rev. Geophys. Space Phys.* **17**, 2032.
Iucci, N., Parisi, M., Storini, M., and Villoresi, G.: 1979, *Nuovo Cimento* **26**, 421.
Jokipii, J. R., Levy, E. H., and Hubbard, W. B.: 1977, *Astrophys. J.* **213**, 861.
Jokipii, J. R. and Kopřiva, D. A.: 1979, *Proc. 16th Int. Conf. Cosmic Rays* **3**, 7.
King, J. H.: 1977, *Inter. Medium Data Book*, NSSDS/WDC-A Greenbelt, Maryland.
Lindblad, B. A. and Lundstedt, H.: 1981, *Solar Phys.* **74**, 197.
Mathews, T., Quenby, J. J., and Sear, J.: 1971, *Nature* **229**, 246.
Moraal, H.: 1976, *Space Sci. Rev.* **19**, 845.
Morfill, G. E., Volk, H. J., and Lee, M. A.: 1976, *J. Geophys. Res.* **81**, 5841.
Nagashima, K. and Morishita, I.: 1980a, *Planetary Space Sci.* **28**, 177.
Nagashima, K. and Morishita, I.: 1980b, *Planetary Space Sci.* **28**, 195.
Pomerantz, M. A. and Duggal, S. P.: 1974, *Rev. Geophys. Space Phys.* **12**, 343.
Rao, U. R.: 1972, *Space Sci. Rev.* **12**, 719.
Shea, M. A. and Smart, D. F.: 1981, *Adv. Space Sci.* **1**, 147.
Shukla, J. P., Shukla, A. K., Singh, R. L., and Agrawal, S. P.: 1979, *Ind. J. Radio Space Phys.* **8**, 230.
Simpson, J. A.: 1963, *Proc. 8th Int. Conf. Cosmic Rays* **2**, 155.
Venkatesan, D., Shukla, A. K., and Agrawal, S. P.: 1982, *Solar Phys.* **81**, 375.
Xanthakis, J., Mavromichalaki, H., and Petropoulos, B.: 1981, *Astrophys. Space Sci.* **74**, 303.
Yoshimura, H.: 1977, *Solar Phys.* **54**, 229.
Zirker, J. B.: 1977, *Rev. Geophys. Space Phys.* **15**, 247.