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Simulated effects at neutron monitor energies: evidence for a 22-year cosmic-ray variation

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Abstract. Determined systematic differences in the overall shapes of successive 11-year modulation cycles (1946–1995) and similarities in the shapes of alternate 11-year cycles seem to be related to the 22-year magnetic cycle and to the polarity reversals of the polar magnetic field of the Sun. This different behaviour of the odd and even solar cycles that are the two parts of the 22-year periodicity is discussed in terms of different processes influencing the transport of cosmic rays from the edges of the heliosphere to the near-Earth region. Taking into account these characteristic features, monthly cosmic-ray data from Inuvik and Climax Neutron Monitor Stations have been used to describe on a general basis the long-term modulation of galactic cosmic-rays during the last three solar cycles (1965–1994) where data are available. With the aid of appropriate selected source functions and calculating the time lag of cosmic-ray intensity against these indices, the modulated cosmic-ray intensity has been simulated with an approximation of 10% during this period. The hysteresis curves applied to the observed modulated as well as to the calculated cosmic-ray intensities with the expected differences between even and odd solar cycles confirm the good approximation of our generalised model. This is derived by the generalisation of Simpson's solar wind model using the diffusion-convection theory.

Key words: inteplanetary medium – Sun: activity – cosmic rays

1. Introduction

The 11-year modulation of cosmic-rays, in anticorrelation with the 11-year solar activity cycle, is well established, although its origin is not fully understood (Forbush, 1958). In addition to this 11-year cycle, there are various features which indicate that a 22-year periodicity in this modulation is also important (Webber and Lockwood, 1988). Among the more important features that seem to have a 22-year periodicity (in addition to an 11-year periodicity) are: the diurnal variation (Thambyahpillai and Elliot, 1953), general asymmetries in the rigidity dependence of the modulation that are different in successive 11-year cycles (Webber et al, 1983), modulation effects that depend on the sign of the particle change and are different in successive 11-year cycles (Garcia-Munoz et al, 1986) etc. Neutron monitor data available now for more than two complete 22-year cycles show evidence for the existence of 22-year periodicity in the cosmic-ray intensity variations (Nagashima and Morishita, 1980b; Mavromichalaki et al, 1988).

It has been pointed out by many researchers that some anomalous phenomena in the solar modulation of cosmic rays have been observed for several years after the solar maximum (1968) in the 20th solar cycle. These phenomena are the abnormality of the modulation rigidity spectra of cosmic-ray intensities (Lockwood and Webber, 1979), the sudden recovery of the intensity (Kuzmin et al., 1977), the poor correlation of the intensities with solar activities (Ashirof et al., 1977) etc. These phenomena were summarised by Nagashima (1977) and interpreted as the result of reversal of the polar magnetic field of the Sun that occurred over the period of mid 1969-mid 1971. Such phenomena in the cosmic-ray intensity have also been observed after solar maximum as well as in the declining phases of the 19th, 21st and 22nd solar cycles (Webber and Lockwood, 1988; Mavromichalaki et al., 1988). Jokipii et al. (1977) suggest that the modulation of the galactic cosmic rays should have a significant component controlled by the state of the interplanetary magnetic field as transported out from the Sun, and hence there should be a solar cycle effect on the drift of cosmic rays in the heliosphere.

The purpose of this contribution is to consider at first some different aspects of the solar modulation during the period 1947–1995 covering five complete solar cycles (18th, 19th, 20th, 21st, 22nd) and to suggest tentative reasons for their different behaviour in different cycles. Examining cosmic-ray monthly values of the Climax and Inuvik Neutron Monitor Stations for the period Jan. 1953 to Dec. 1994, similarities have been found between modulation phenomena of galactic cosmic rays during solar activity cycles of the same type (even or odd). This

Send offprint requests to: H. Mavromichalaki fact supports a possible effectiveness of the Hale cycle (about a 22-year variation connected with the heliomagnetic field). Obtaining useful information from this consideration, we have simulated the long-term modulation of galactic cosmic rays during the last three cycles, where data are available, according to the method by Mavromichalaki et al. (1990). The computed values follow the observations fairly well, and the observed deviations in cosmic-ray residuals have appeared during or after reversals of the polar magnetic field of the Sun. According to these results, one should expect a 22-year variation in cosmic-ray intensity.

2. Evidence of a 22-year cosmic-ray variation

Neutron Monitor records available for more than forty years show how cosmic radiation is excluded from the solar system at times of maximum solar activity. Monthly cosmic-ray values corrected for pressure at Climax Neutron Monitor Energies (2.96 GV) from 1953 to the end of 1995 with monthly values of the sunspot number from 1946 to 1995 (Solar Geophysical Data Reports, 1995) are presented in Fig. 1. The epochs of the solar polar magnetic field reversals are indicated, and the notations $\vec{M} \uparrow\uparrow \vec{\Omega}$ and $\vec{M} \uparrow\downarrow \vec{\Omega}$ indicate the magnetic moment parallel and antiparallel to the angular velocity axis of rotation of the Sun respectively (Otaola et al., 1985; Page, 1995).

There are differences in solar activity from cycle to cycle. There are series of cycles with very high activity level (19th, 21st) as well as quite low activity (20th, 22nd). A different behaviour between even and odd solar cycles is presented in solar activity (Dodson and Hedeman, 1975), where even sunspot cycles are characterised by two well-defined "stillstands" in the level of activity during the declining phases of such cycles. When the rises and the declines are compared, most cycles are very asymmetrical, with fast increase and much slower decrease. There are also symmetrical cycles. Generally the rise is faster and the decline longer for higher cycles, although that is not always true. Thus, there are essential differences in the behaviour of the Sun during the declining phases of different solar cycles (Storini, 1995).

Looking at the current solar cycle (22nd), we observe that this cycle reached its maximum rapidly, about one year before expectations and stayed very long from half of 1989 through to the end of 1991, in a fast maximum phase with a secondary maximum in 1991, only slightly lower than the primary one. Thereafter, the cycle declined steeply, but the decay became slower since late 1992. An explanation of this behaviour according to Svetska (1995) is that the most powerful events can occur only before or after the maximum, when activity is high enough to produce large energy storage in interplanetary space and Earth's magnetosphere, but not so high that the storage is disrupted too early in consequence of another activity nearby. This explanation is not necessarily be the correct one.

As concerns the behaviour of the cosmic-ray flux as measured by Neutron Monitor near the Earth, cycles No 20 and 22 differed from cycles 19 and 21. In cycle No 20, the cosmic-ray flux became high shortly after the cycle maximum and stayed high for seven years (1972–1978). In cycle No 22, the flux stayed high for about three years (1992–95) with a giant secondary minimum in 1991. This transient decrease originating in June 1991 reduced the cosmic-ray intensity back to nearly the same level as that at the 11-year intensity minimum in 1990 (Webber and Lockwood, 1993). In cycles 19 and 21, the flux rose slowly and peaked early, close to the cycle minimum for only one year (1965, 1986 respectively). So we have cycles characterised by a "saddle-like" shape and others characterised by a "peak-like" shape.

We underline that the cosmic-ray recovery of the 20th and 22nd solar cycles is rather rapid, whereas the recovery of cycles 19 and 21 were completed over a long period (about 4–5 years). Ahluwalia (1995) has shown that the recovery of cosmic-ray intensity follows two distinct patterns. During odd solar activity cycles, when magnetic polarity is negative in the northern hemisphere ($qA < 0$), recovery is completed in 5 to 8 years, while the recovery period is less than half as much for even cycles (when $qA > 0$). The rapid recovery seems to set in following the reversal of the polar magnetic field unless interrupted by solar activity (as for cycle 22). Gnevyshev (1967) suggested that the 11-year solar cycle consists of two parts, one peaks at solar activity maximum and the other 2–3 years later, and the most energetic events appear during the second maximum.

The differences between solar cycles, or at least some of them,seem to be due to different behaviours of odd and even solar cycles, i.e. of the two parts of the basic 22-year solar periodicity. Otaola et al. (1985) have shown that the different behaviours of the cosmic-ray intensity during even and odd solar cycles is due to the parallel and antiparallel states of polarity of the polar magnetic field of the Sun relative to the galactic magnetic field. Their analysis shows a tendency towards a regular alternation of cosmic-ray intensity cycles with double and single maxima.

The polarity of the solar field reverses sign about every 11 years near the time of maximum solar activity or minimum cosmic-ray intensity. Thus, successive activity minima are characterised by a different solar field polarity. Table 1 shows the times of magnetic field polarity change, completing the work of Webber and Lockwood (1988) along with some of the features of the modulation that we have noted for the various cycles.These features can certainly be related to the 22-year magnetic field cycle. To understand how cosmic-rays move in the heliosphere under the influence of drifts, one needs to recognise the importance of the current sheet that divides the heliosphere into two hemispheres containing oppositely directed magnetic fields (Kota and Jokipii, 1991).

3. Hysteresis effect

The 11-year modulation of the cosmic-ray intensity shows some time lag behind the solar activity, in other words some kind of hysteresis effect against the activity (Moraal 1976; Mavromichalaki et al 1990 etc). In this paper, we show that there is a characteristic difference between even and odd solar cycles concerning the time lag between cosmic-ray intensity and the proxy indices of solar activity. A correlated analysis be-

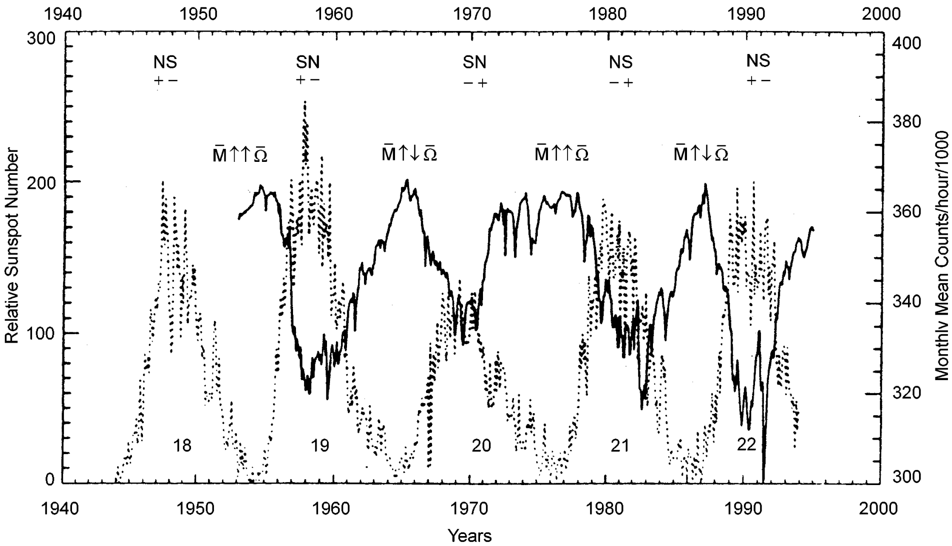

Fig. 1. Pressure-corrected monthly cosmic-ray intensities at Climax Neutron Monitor energies together with monthly values of sunspot number from Jan. 1946 to Dec. 1995. The polarity reversals of the solar magnetic field are indicated.

Table 1. Solar magnetic field polarity

Polar Field Changeover	Solar Field Polarity	Drift Effects (Positive Particles)	Cosmic Ray Intensity at Solar Activity Minimum
	north polar field inward	inward along current sheet	
N - to + Feb. 1947 S + to - Apr. 1948			
	outward	down from polar regions and outward along the current sheet	flat maximum intensity from 1952 to 1954
N + to - Nov. 1958 S - to + May 1957			
	inward	inward along current sheet	sharply peaked maximum intensity in 1965
N - to + Feb. 1971 S + to - Sep. 1969			
	outward	down from polar regions and outward along current sheet	flat maximum intensity from 1972 to 1977
N + to - May 1980 S - to + Sep. 1980			
	inward	inward along current sheet	sharply peaked maximum intensity in 1987
N - to + Jan. 1990 S + to - Iun. 1991			
	outward	down from polar regions and outward along current sheet	flat maximum intensity from 1993 to 1995

tween the monthly values of the cosmic-ray intensity at Neutron Monitor Energies for the three solar cycles (20th, 21st, 22nd) and the solar activity is indicated by
the sunspot number Rz
the grouped solar flares Nf and
the Ap index
for the time period 1965–1995 as a function of the cosmic-ray intensity lag with respect to these parameters (Hatton, 1980; Mavromichalaki and Petropoulos,1987). The monthly values of the sunspot number, solar flares and Ap index during the period examined in this work are taken from the Solar Geophysical Data Reports. Monthly data from the two Neutron Monitor Stations, Climax (2.96 GV) and Inuvik (0.16GV) have been used. The pressure-corrected cosmic-ray data of each station for the period 1965–1995 were normalised with the intensity taken equal to 1.00 at solar minimum (May 1965) and equal to 0.00 at solar maximum (June 1991). The correlation coefficients for different time lags calculating over the three solar cycles are presented in Fig. 2. Each cycle has appeared separately in previous works (Mavromichalaki et al., 1984; Mavromichalaki et al., 1988; Marmatsouri et al., 1995). We can see that the cross-correlation coefficient for the sunspot number is at a maximum

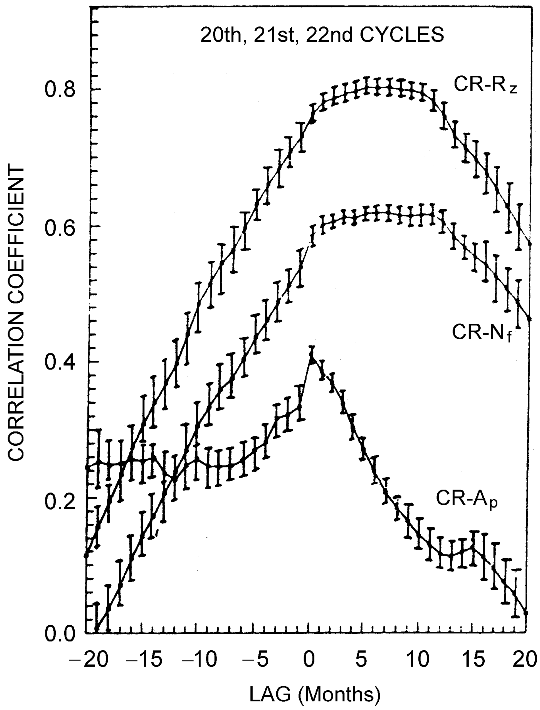

Fig. 2. Correlation coefficients between monthly cosmic-ray intensity and sunspot number, grouped solar flares and Ap-index as functions of cosmic-ray intensity with respect to these indices for the time period 1965–1995. The statistical errors are also indicated.

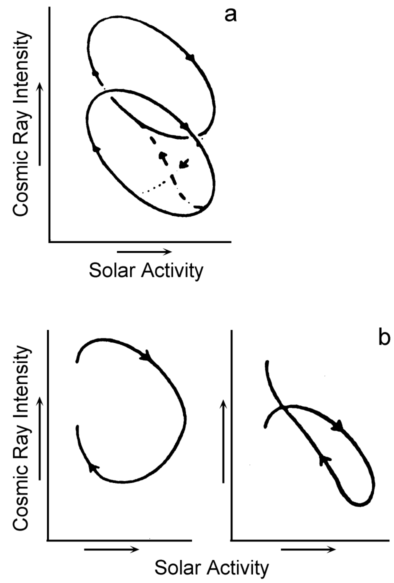

Fig. 3a and b. Schematic solar-cycle dependence of hysteresis curves of cosmic-ray intensity versus solar activity due to the polarity reversal of the solar polar magnetic field. (Nagashima and Morishita, 1980b)

at a time lag of five months and for the grouped flares is at a maximum at a time lag of six months. The correlation coefficient of cosmic-ray intensity and geomagnetic activity expressed by Ap index does not show a pronounced maximum. One can distinguish two peaks: one at zero months and another at 14 months. This is consistent with the results of previous solar cycles (Balasubrahmanyan, 1969; Mavromichalaki and Petropoulos, 1984) where Bartels's Ap index correlates with the cosmic-ray intensity without pronounced phase lags or with the two maxima.

The time lags of cosmic rays corresponding to the cross-correlation coefficient of each parameter for the cycles 20, 21 and 22 separately and for the three solar cycles are given in Table 2. According to Fisher's transformation of relation coefficient significance, the estimated correlation coefficients for our data series are at a 99%. It is noteworthy that the sunspot number phase lag for the 21st solar cycle is remarkably large (16 months), whereas it is small in the 20th and 22nd solar cycles (2 months and 4 months respectively), which are even cycles (Mavromichalaki et al., 1988). This gives us an evidence that there is a distinction between even and odd solar cycles concerning the hysteresis phenomenon. To clarify this distinction, we present the time lag of sunspot numbers with respect to cosmic-ray intensity for the last six solar cycles in Table 3. This result for the first three solar cycles has been adapted from Nagashima and Morishita (1980b), while the hysteresis for the last three cycles has been computed for the purposes of this paper. Inspecting the whole set of results, we can clearly distinguish between even and odd solar cycles concerning the sunspot number time lag. This is due to the 22-year variation in the time-lag already found by Nagashima and Morishita (1980b) and Otaola et al. (1985). Indeed particles reach the Earth more easily when their access route is by the heliospheric polar regions than when they gain access along the recurrent sheet. In this case, as the route of access becomes longer due to the waviness of the neutral sheet (Kota and Jokipii, 1991), the time-lag is also longer as one would expect from theoretical considerations. This model can't explain, however, the double-maximum structure of the even cycles.

The Table 2 shows that during the 21st solar cycle the solar flares $< 1B$ affected mainly the cosmic-ray modulation and not the sunspot number, as in the 20th solar cycle. Storini (1995) underlined that the anticorrelation between cosmic-ray data and sunspot numbers is very high for all phases considered, excepting the declining ones of cycles 20 and 21, when high-speed solar wind streams coming from coronal holes affected the cosmic-ray propagation. The sunspot parameter is not the right index for solar-induced effects in the interplanetary medium. The anticorrelation during the 22nd cycle between cosmic-rays and solar magnetic field is very high (0.85) (Burlaga et al., 1993; Marmatsouri et al., 1995)

If the effect of the polarity reversal is superposed on the hysteresis effect, the hysteresis curves split into two loops, as shown by the solid lines in Fig. 3a of Nagashima and Morishita (1980b). The upper and lower loops correspond respectively to parallel and antiparallel states of polarity to the galactic magnetic field. Practically, however, as the reversal is supposed to occur around every solar maximum (Babcock, 1961), the transition from the upper to the lower loop and vice versa can be expected to occur alternately every eleven years as shown by the dotted and chained lines in the figure. If we divide the hysteresis

Table 2. Cross-correlation coefficients and the corresponding time lags for each of the solar cycles 20, 21 and 22 separately and for the three cycles.

	20th Cycle		21st Cycle		22nd Cycle	
Indices	r	Lag(m)	r	Lag(m)	r	Lag(m)
Sunspot number	-0.88 ± 0.01	2	-0.87 ± 0.01	16	-0.90 ± 0.01	4
Solar Flares≥1N	-0.76 ± 0.02	4	-0.87 ± 0.01	17	-0.81 ± 0.02	4
Solar Flares≥1B			-0.70 ± 0.02	6		
Proton Events	-0.48 ± 0.02	4				
Streams	-0.30 ± 0.02	3	-0.30 ± 0.02	5	-0.20 ± 0.02	3
Corot. Streams			0.17 ± 0.03	16	-0.10 ± 0.02	0
Flare-G.Streams			-0.51 ± 0.02	16	-0.36 ± 0.02	3
Mean Solar Field					-0.85 ± 0.01	2
A_p-Index	-0.20 ± 0.02	0	-0.45 ± 0.02	0	-0.58 ± 0.02	0
	-0.33 ± 0.02	-12	-0.48 ± 0.02	-16	-0.38 ± 0.02	-14

20th, 21st, 22nd cycles (1964 -1994)		
Indices	r	lag(m)
Sunspot number	0.81 ± 0.01	5
Grouped Solar Flares	0.62 ± 0.01	6
Streams	0.10 ± 0.02	2
A_p-Index	0.41 ± 0.02	0
	0.26 ± 0.02	-14

Table 3. Solar cycle dependence of time lag of the cosmic-ray intensity behind the sunspot number.

Solar cycle	17	18	19	20	21	22
Time-lag (Months)	9	1	10-11	2	16	4

curve into two at solar minima, so that each curve corresponds to each period of solar cycle number, then the divided curves describe respectively the wider and narrower loops as shown in Fig. 3b. The upper panel of Fig. 4 shows the observed hysteresis curves for three solar cycles for the Inuvik cosmic-ray data. The reversals of the solar polar magnetic field are indicated. These curves clearly show respectively the above-mentioned patterns during solar cycles of the same type (even or odd). The curves during the even cycles are narrower than the curves of the odd cycles, while the existence of the secondary maximum is obvious and occurs after the polarity reversals.

4. Cosmic-ray simulation

Previous works (Xanthakis et al., 1981; Mavromichalaki et al., 1990; Marmatsouri et al., 1995) proposed an empirical model to describe the long-term cosmic-ray modulation during cycles 20, 21 and 22. We have now attempted to give a generalised model applied over the three solar cycles, as data are not available for the time before. This generalised model is derived by a generalisation of Simpson's solar wind model using the diffusion-convection-drift model (Nagashima and Morishita, 1980a). According to this, the modulated cosmic-ray intensity as it is measured at Neutron Monitor Stations can be computed by the difference between the galactic cosmic-ray intensity expressed by a constant C and the sum of some source functions appropriately selected from the solar and interplanetary indices that affect the cosmic-ray modulation (see discussion). The empirical relation is given by the following expression:

$$I = C - 10^{-3}(a_1 R_z + a_2 N_t - a_3 A_p) \quad (1)$$

where the constant C depends linearly on the cut-off rigidity of each station, Rz, Nf, Ap are the solar-terrestrial parameters incorporating the time-lag and i (i=1 to 3) are factors calculated by the RMS-minimisation (2.5, 1.8, and 0.5 respectively). The observed and calculated values of the cosmic-ray intensity for the Inuvik and Climax Neutron Monitor stations are presented in Figs. 5 and 6 respectively. The residuals are also indicated. The standard deviation between the observed and calculated values is about 10%, which suggests a very good approximation. It is noteworthy that this formula simulates fairly well the cosmic-ray intensity observed at the Earth during the onset and the declining phase of the solar cycles, whereas it is not so good during the maximum phase of solar activity. This is expected, because during the maximum phase the solar magnetic polarity usually changes configuration (Fig. 5 and 6). It is known that this change takes place over a period of several months. For example, in the last cycle it seems to have had a duration longer than one year (Webber and Lockwood, 1993). The hysteresis curves of the values calculated by Eq. (1) of the cosmic-ray intensity at Inuvik with the sunspot number are also presented in the lower panel of Fig. 4. We underline that these curves follow the hysteresis curves of the observed values of cosmic-ray intensity (upper panel). Loops for odd and even cycles correspond respectively to the left and right loops in Fig. 3b. The time lag of cosmic-ray intensity clearly shows a 22-year variation that is greater in odd number cycles than in even cycles. Comparing with the results of the correlation method (Table 2) we note that we have the same characteristics quantitatively in spite of their difference in the observation method. This fact also suggests that the 11-year modulation of the comic-ray intensity has been modulated by some disturbance with the 22-year periodicity through the three solar cycles. The sunspot number has no ability to produce such a 22-year variation (Nagashima and Morishita, 1980a).

5. Discussion and results

The solar modulation of galactic cosmic-rays describes the changes due to the solar influence on the isotropic and constant distribution of energetic particles from local interstellar space. The understanding of the modulation is still based on the standard model of diffusion, convection and adiabatic deceleration effects, where the path of individual particles through

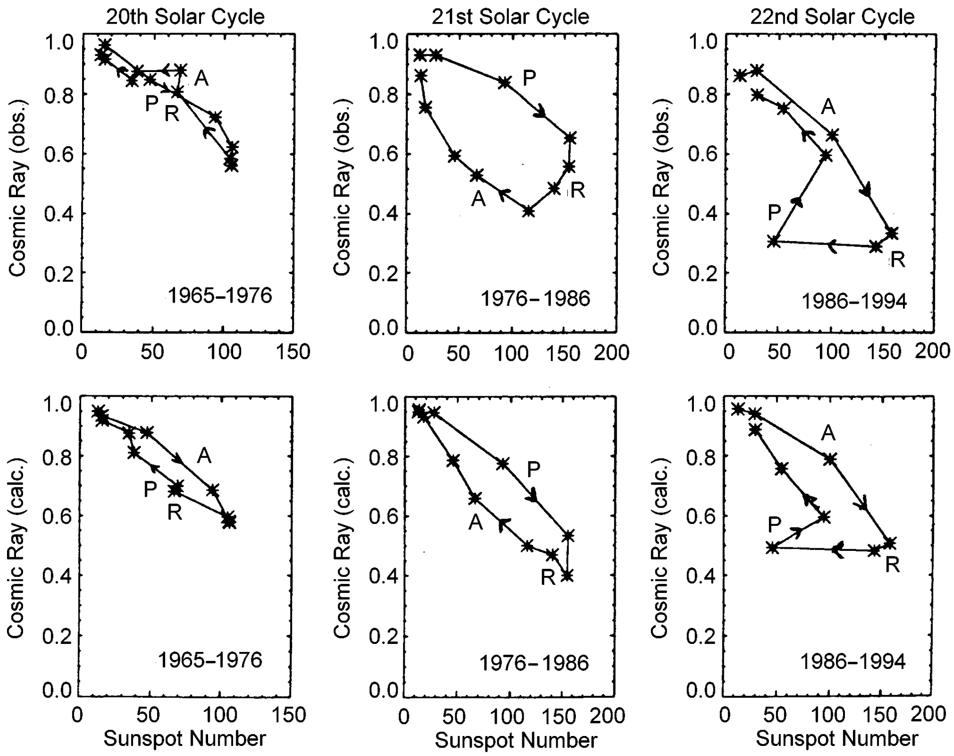

Fig. 4. Observed (upper panel) and calculated (lower panel) hysteresis curves for the three last solar cycles. Yearly mean intensities from Inuvik Neutron Monitor Station. The reversals from parallel to antiparallel state of the magnetic field and vice versa are indicated (P: parallel, A: antiparallel and R: Reversal).

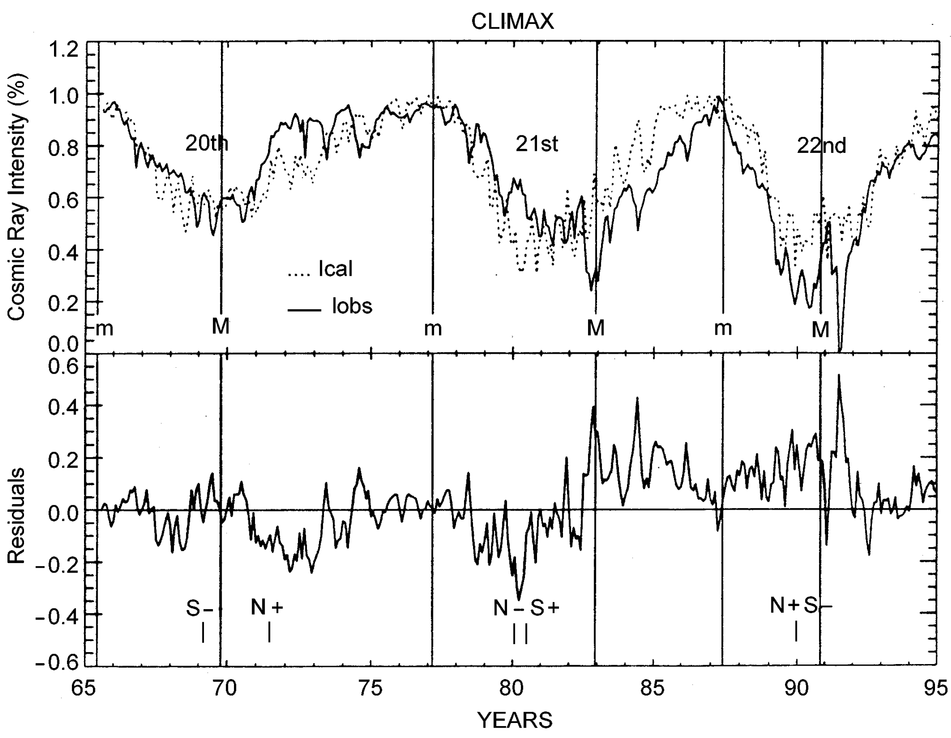

Fig. 5. Observed and calculated monthly cosmic-ray intensities at Climax Neutron Monitor Energies during the 20th, 21st and 22nd solar cycles. The residuals are also presented.

the heliosphere is determined by the interplanetary magnetic fieldlines including drift processes. This leads to characteristic differences between adjacent solar cycles due to the different polarity of the solar and large-scale interplanetary magnetic fields (Kunow, 1991). The polarity of the solar field reverses sign about every 11-years near the time of maximum solar activity or minimum cosmic ray intensity. Thus successive activity maxima are characterised by different solar field polarity. In this work searching the last four solar cycles we have noted systematic differences between successive 11-year cycles and similarities between alternate 11-year cycles which are consistent to the 22-year magnetic cycle. When the solar polar field points into the northern hemisphere, i.e. during the odd cycles, we observe a "pointed" type maximum, while during the even cycles, a "mesa"-type maximum appears. The recovery phase of the odd cycle is characterised by a relatively long-lasting (6–8 years) smoothed increase, while the even cycle is characterized by a relatively rapid (about 3 years) increase (Mavromichalaki et al., 1988: Ahluwalia, 1995). The existence of two maxima in solar indices during the even solar cycles is reported by many authors (Mavromichalaki et al., 1988). The mean time lag of the cosmic-ray intensity behind the solar activity is estimated at about 5 months for the period 1965–1994. Thus, considering as a mean solar wind speed 500 km/s, we estimate that the mean modulation barrier that is the limits the heliosphere is (70 AU (Simpson and Wang, 1967). This value is consistent with most estimates, which place the modulation barrier at $\sim$ 80 AU. These basic characteristics of a solar cycle and its declining phase, according to Lin et al. (1994), can be summarised as follows: One or two years after a sunspot maximum, a new solar cycle begins shortly after the polar field reversal of the Sun. The activity of the previous cycle moves towards the equator, leaving an empty space at high latitudes for the formation of polar coronal holes which begin to grow reaching their maximum extent shortly before the old cycle minimum. At solar maximum, the polar regions are occupied by an equal number of positive and negative magnetic elements. As the cycle progresses towards sunspot minimum, the magnetic field elements in each polar region change to predominantly one polarity, positive on one pole and negative on the other.

The diffusion-convection and adiabatic deceleration theory (Gleeson and Axford, 1967) of galactic cosmic rays into a spherically symmetric solar wind model would lead to a long-term variation. In the light of this model, the modulation is 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, 1980a; Xanthakis et al., 1981; Mavromichalaki and Petropoulos, 1987) studing previous solar cycles have shown that the cosmic-ray modulation can be described by the following integral equation, derived from a generalisation of Simpson's coasting solar wind model (1963) as:

$$I(t) = I - \int f(r)S(t-r)dr \tag{2}$$

where I and I(t) are, respectively, the galactic (unmodulated) and modulated cosmic ray intensities, S(t-r) the source function representing some proper solar activity index at a time t-r (r(0), and f(r) the characteristic function that 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 last three solar cycles can be described on a monthly basis by the source function of Eq. (2) expressed by a linear combination of three indices: the sunspot number Rz, the solar flares of importance (1B Nf, and the geomagnetic index Ap. The characteristic function f(r) of all these indices has a constant value during a 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 properly selected parameters which cause the disturbances in interplanetary space and thus modulate the cosmic-ray intensity. This model reproduces to a certain degree the cosmic-ray modulation, which will be very useful to cosmic-ray research.

To estimate the degree of agreement between the observed cosmic-ray intensities and those calculated according to this model, we computed the residuals between the observed and calculated values, presented in Figs. 5 and 6. Our model describes the cosmic-ray long-term modulation very well for the time period 1965–1995, three consecutive solar cycles. Neverthless, we note a deviation from the observed values which becomes remarkable during the declining phase of the 21st solar cycle and also around the maximum of the 21st and 22nd solar cycles. Polarity reversals of the polar solar magnetic field occurred around these periods. These residual values may be explained by the following interpretation of Ahluwalia (1979). A secondary maximum of the even solar cycles is observed 1–2 years after reversal from negative north pole to positive north pole. This leads from a closed heliosphere magnetic topology to an open one. Particles of the interstellar medium get into the heliosphere by travelling through the polar field lines of the Sun. In the opposite case, the diffusion mechanism is the most prominent one (Smart and Shea, 1981). During the solar maximum of the 21st cycle, a reversal of the solar polarity from $\vec{M} \uparrow\uparrow \vec{\Omega}$ to $\vec{M} \uparrow\downarrow \vec{\Omega}$ occurred. The north pole of the Sun became negative, resulting in an inward magnetic field. A closed magnetic configuration of the heliosphere was formed. The result was weaker in cosmic-ray intensity than expected from the proposed model.

On the other hand, Popielawska (1995) noted that near maximum solar activity, a transient mode of modulation manifests itself as a distinct phenomenon distinguished by formation of so-called hysteresis "loops" on correlation plots for low- versus high-rigidity cosmic-ray intensity changes. These hysteresis loops close fully at high modulation levels. The solar field evolves from a roughly dipole like configuration at solar minimum to a complex state at solar maximum when the polar fields inverse. The duration of this situation is about four years for the 22-nd solar cycle (Hoeksema, 1991). Perhaps an improvement of our model using for example a new source function with the tilt of the heliospheric current sheet (for the onset and declining phase) and/or the transient phenomena (for the solar maximum) that are highly correlated with the cosmic-ray intensity will give a more appropriate description of galactic cosmic-ray intensity (unmodulated). This proposed model would give an integrated model for the cosmic-ray modulation for the coming solar cycles.

6. Conclusions

We can summarise the following:

1.- A distinction between even and odd solar cycles, as well as between the declining and ascending phases of them, is well established. As concerns the solar activity there are symmetrical and asymmetrical solar cycles where generally the rise is faster and the decline is longer. As concerns the cosmic-ray modulation during solar cycles, the shapes of the cosmic-ray curves

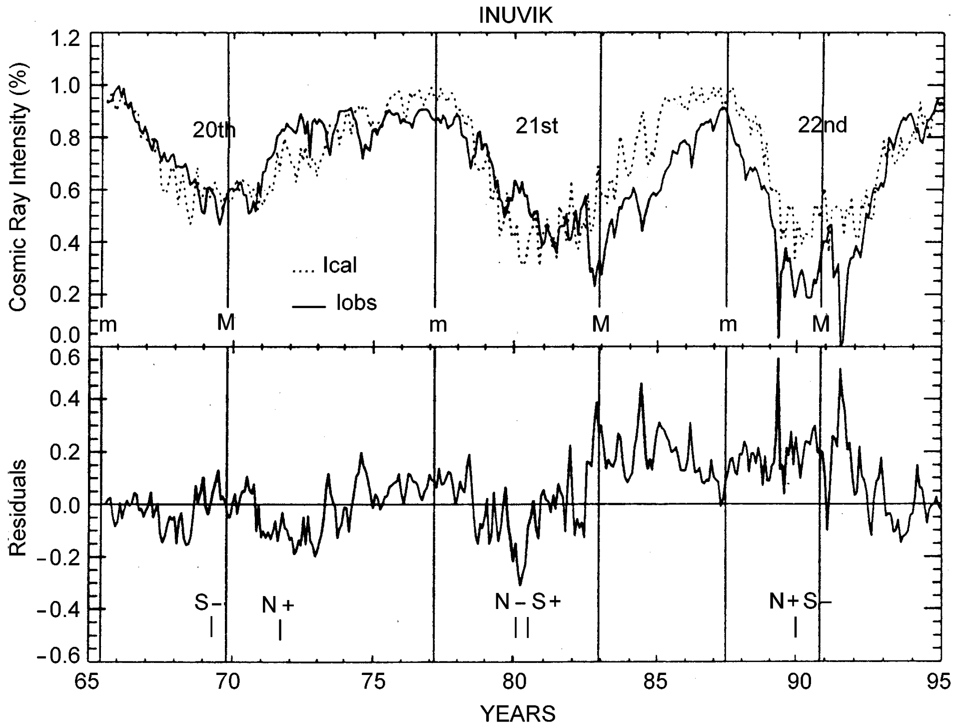

Fig. 6. Observed and calculated monthly cosmic-ray intensities at Inuvik Neutron Monitor Energies during the 20th, 21st and 22nd solar cycles. The residuals are also presented.

of the even cycles differ systematically and markedly from the shape of the odd cycles. The odd cycle is characterised by a simple and relatively smooth increase to the maximum (7.5 yr), whereas the even cycles on the average are characterised by two maxima. The first maximum is reached relatively rapid, after the previous minimum in cosmic-ray intensity (3–4 yr). The second, the main and also more developed, tends to occur at the same time in the cycle as the maximum of the odd cycle.

2.- A proposed model described the long term modulation of cosmic rays over three solar cycles closely relates the long to the short term cosmic-ray modulation, and it is able to explain the long-term modulation overcoming the difficulties that arise when the interplanetary parameters are assumed almost constant in the quasi-stationary convection-diffusion model. The results obtained are very satisfactory through the whole period under study, which covers three solar-cycles. It is assumed that this model perhaps will give an integrated model for the cosmic-ray modulation for the coming solar cycles.

3.- The hysteresis loops obtained from the cosmic-ray data of Inuvik, as well as those obtained from Eq. (1) present the expected differences between even and odd cycles. The proposed model works very well through the three solar cycles, denoting the transition from the parallel to the antiparallel state of the solar magnetic field and vice versa in the hysteresis curves.

All these solar cycle phenomena occurring during even and odd solar cycles give evidence for the existence of a 22-year variation in cosmic-ray intensity. This interpretation is based on a working hypothesis that when the polar magnetic field of the Sun is nearly parallel to the galactic magnetic field, they could easily connect, so that galactic cosmic-rays, especially those of low rigidities, could intrude more easily into the magnetosphere along the magnetic lines of force, as compared with those in the antiparallel state of the magnetic fields. Different processes then influence cosmic-ray transport in the heliosphere. During even cycles, convection plays the most important role, while diffusion dominates during odd cycles. In more recent times, the effect of gradient drifts in the oppositely-directed north and south heliospheric magnetic fields has received much attention (Mckibben, 1990; Potgieter, 1994). The drift picture of Kota and Jokipii (1983) fits naturally into the 22-year periodicity of the solar magnetic field. A further study of this model with more suitable source functions that can be associated with the electromagnetic properties in the modulating region will lead us to a better understanding of the relations among coronal structure, interplanetary structure and cosmic rays.

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