HALE-CYCLE EFFECTS IN COSMIC-RAY INTENSITY DURING THE LAST FOUR CYCLES

H. MAVROMICHALAKI[1], A. BELEHAKI[2], X. RAFIOS[1] and I. TSAGOURI[1]
[1] *Nuclear and Particle Physics Section, Athens University, Solonos 104, Athens GR-10680*
[2] *Athens National Observatory, Space Research Inst., Metaxa & V. Pavlou, P. Penteli GR-15236*

(Received 20 October, 1996; accepted 18 December, 1996)

Abstract. Monthly cosmic-ray data from Inuvik (0.16 GV) and Climax (2.96 GV) Neutron Monitor stations has been studied with the aid of solar activity parameters for the time period 1947–1995. Systematic differences in the overall shape of successive 11-year modulation cycles and similarities in the alternate 11-year cycles seem to be related to the polarity reversals of the polar magnetic field of the Sun. This suggests a possible effectiveness of the Hale cycle during even and odd solar activity cycles. Our results can be understood in terms of open and closed models of the heliosphere. Positive north pole of the Sun leads to open heliosphere where particles reach the Earth more easily when their access route is by the heliospheric polar regions (even cycles) than when they gain access along the current sheet (odd cycles). In this case as the route of access becomes longer due to the waviness of the neutral sheet, the hysteresis effect of cosmic-rays is also longer. This interpretation is explained in terms of different contributions of convection, diffusion and drift mechanisms to the whole modulation process influencing cosmic-ray transport in the heliosphere.

1. Introduction

From Neutron Monitor data available now for more than forty years there is evidence that there is a 22-year periodicity in the cosmic-ray intensity variations in addition to the 11-year cycle. For example, the period of maximum cosmic-ray intensity extended over a 5 to 6-year period from 1972 to 1978 around the 1976 solar activity minimum, whereas the maximum cosmic-ray intensity was sharply peaked around the 1965 activity minimum (Jokipii and Thomas, 1981). The cosmic-ray intensity also in 1987 shows a very sharp maximum similar to that seen in 1965 followed by a pronounced decrease throughout the rest of the year and the period of cosmic-ray maximum seems to be flat from 1993 till today. Overall, the 22-year features of this modulation appear to be quite prominent relative to the 11-year modulation when it is possible to compare the modulation over two 22-year cycles.

Nagashima and Morishita (1980) interpreted these phenomena as the result of the polarity reversal of the polar magnetic field of the Sun which occurs around every solar maximum. Ahluwalia (1995) has pointed out that the emerging solar polar magnetic field regime has a significant influence on the shape of the profile of the eleven year variation of cosmic-ray intensity.

The purpose of this paper is to reconfirm the existence of this 22-year variation at Neutron Monitor Energies and illustrate the importance of this in addition to the well known 11-year cycle. A further study of its nature is tried with emphasis upon its relation to the polarity reversal of the polar magnetic field of the Sun.

Astrophysics and Space Science **246:** 7–14, 1997.

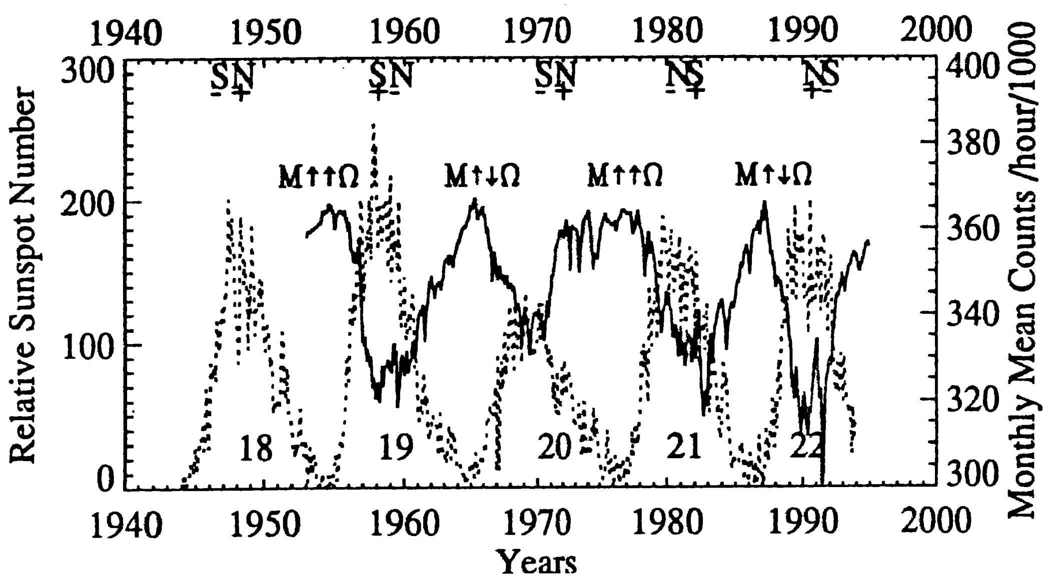

Figure 1. Monthly values of the cosmic-ray intensity at Climax Neutron Monitor Energies (1953–1995) with the monthly sunspot number (1947–1995). The times of the solar polar magnetic field reversals are indicated.

2. Neutron Monitor Observations

Examining Neutron Monitor records from Climax (2.96 GV) and Inuvik (0.19 GV) Stations we can show how cosmic radiation is excluded from the solar system at times of maximum and minimum solar activity (Figure 1). The used data covers five cycles (18–22) for the solar activity and four cycles (19–22) for the cosmic-ray intensity. The notation **M** $\uparrow\uparrow$ $\boldsymbol{\Omega}$ and **M** $\uparrow\downarrow$ $\boldsymbol{\Omega}$ indicate the magnetic moment parallel and antiparallel to the angular velocity axis of rotation of the Sun respectively.

As concerns the behaviour of cosmic-ray flux as measured by Neutron Monitors near the Earth cycles No 20 and 22 are differed from cycles 19 and 21. In cycle No 20 the flux became high shortly after the cycle maximum and stayed high for seven years and in cycle No 22 the flux stayed high for about three years with a giant secondary maximum 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 was rising slowly and peaked shortly, close to the cycle minimum for only one year. So we have cycles characterized by a 'saddle-like' shape and other ones characterized by a 'peak-like' shape.

We can also underline that the cosmic-ray recovery of the 20th and 22nd solar cycles is rather rapid, whereas the recovery of the cycles 19th and 21st were completed in 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 polar magnetic polarity in northern hemisphere is negative the recovery is completed in 5 to 8 years, while for even cycles the recovery period

Table I
Solar cycle dependence of the time-lag of 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

is reduced to less than half as much. A complementary feature of these patterns are the 'pointy type' and the 'mesa type' maxima in cosmic-ray intensity respectively.

The different behaviour between $\mathbf{M} \uparrow\uparrow \boldsymbol{\Omega}$ and $\mathbf{M} \uparrow\downarrow \boldsymbol{\Omega}$ cycles is also shown in the time-lag of cosmic-ray intensity behind solar activity as measured by the relative sunspot number (Table I). This 22-year variation, already found by Nagashima and Morishita (1980) and Mavromichalaki *et al.* (1988) in which time-lag is greater in $\mathbf{M} \uparrow\downarrow \boldsymbol{\Omega}$ cycles (odd) than in $\mathbf{M} \uparrow\uparrow \boldsymbol{\Omega}$ cycles (even) shows that particles reach the Earth more easily when their access route is by the heliospheric polar regions than when they gain access along the current sheet. In this case as the route of access becomes longer due to the waviness of the neutral sheet the time lag is also longer as one would expect from theoretical considerations.

A clear two-maxima structure is appeared during the even cycles, while the one minimum structure is not so distinct. Gnevyshev (1977) suggested that all the 11-year solar cycles consist of two parts, one peaks at solar activity maximum and the other one 2–3 years later and the most energetic events appear during the second maximum. The analysis of Otaola *et al.* (1985) shows a tendency towards a regular alternation of cosmic-ray intensity cycles with double and single maxima. Feminella and Storini (1995) based on data of the Sun as a star suggest that the occurrence of low and high-energy activity phenomena have a different shape during the 11-year cycle. The former is characterized by a single-peaked cycle, while the later, particularly when long duration phenomena are considered, show a double-peaked structure.

The most characteristic morphological differences between odd and even solar cycles are summarized in Table II. Nowadays we are sure that all the differences between solar cycles or at least some of them are due to the two parts of the basic 22-year solar periodicity. Otaola *et al.* (1985) have shown that this different behaviour is due to the discrete states each corresponding respectively to the parallel and antiparallel states of the polarity of the solar polar magnetic field to the galactic magnetic field.

3. Hysteresis Effect

It is well known that the 11-year variation of cosmic-ray intensity shows some kind of hysteresis against the solar activity. According to Nagashima and Morishita

Table II
Morphological differences between odd and even solar cycles

Odd cycles	Even cycles
	• Two minima structure
• The rising is slow and peaks shortly close to the cycle minimum	• The flux becomes high shortly after the cycle maximum and stays high for a long time.
• 'Saddle-like' type shape	• 'Peak-like' type shape
• 'Mesa' type maximum	• 'Point' type maximum
• Long recovery time (6–8 yrs)	• Rapid recovery time (2–3 yrs)
• Large time-lag	• Small time-lag

(1980), if the effect of the polarity reversal is superposed on this effect, the hysteresis curve splits into the two loops which correspond respectively to the parallel and antiparallel states of polarity to the galactic magnetic field. Transition from one to the other takes place after the polarity reversal in every solar maximum (Babcock, 1961). If we divide the hysteresis curve into two at solar minima so that each curve corresponds to each period of solar cycle number, then the divided curves describe respectively wider and narrower loops.

The observed hysteresis curves of the cycles 19 and 21 derived from the Climax cosmic-ray intensity are narrower than the corresponding ones of the cycles 20 and 22 as it is shown in Figure 3. These curves clearly show the above mentioned characteristic patterns every 22-years and seem to support the working hypothesis at least qualitatively.

To demonstrate more quantitatively the observed characteristics of the solar cycles, the time-lag of cosmic-ray intensity behind the sunspot number for each solar cycle which is derived from their monthly values by the lag correlation method is shown in Table I. The time-lag for the cycles 17 and 18 has been estimated by Nagashima and Morishita (1980) using ion chamber data. The time-lag clearly shows a 22-year variation and is greater in odd number cycles than in even cycles. These values in odd cycles (17, 19, 21) or in even cycles (18, 20, 22) are almost the same as each other. This suggests that the hysteresis curves for odd and even solar cycles of Figure 3 can be considered to show the same characteristics with the Table I even quantitatively in spite of their difference in the observation method. They also suggest that the 11-year modulation of the cosmic-ray intensity has been modulated by some disturbance with 22-year periodicity through four solar cycles.

4. Closed and Open Heliosphere Models

The different cosmic-ray behaviour of odd and even solar cycles related to the solar polar magnetic field reversal requires that this must connect the heliosphere to the

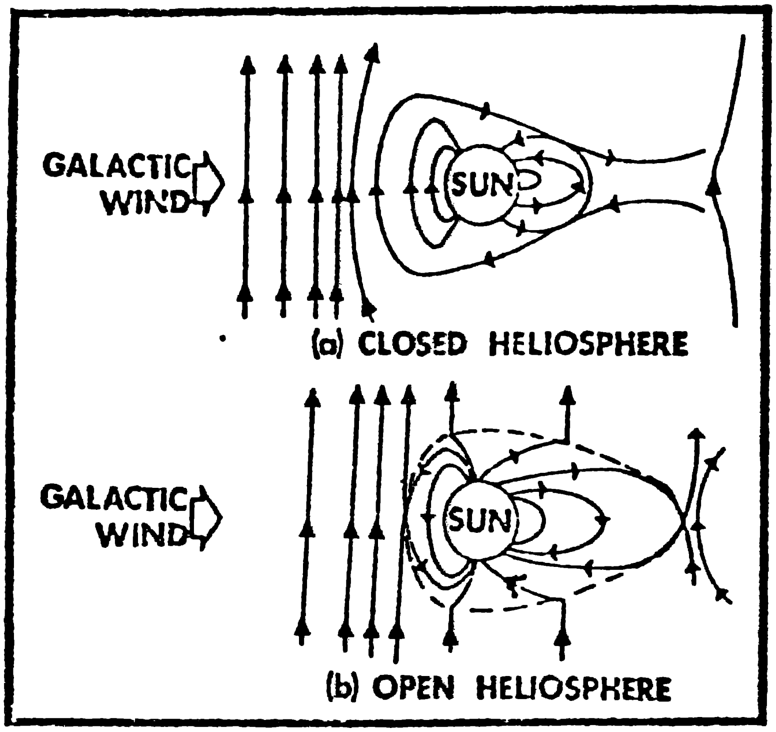

Figure 2. Closed (a) and open (b) heliosphere configurations.

interstellar medium in such a manner as to make it easier for interstellar cosmic-rays to get in. This leads to suggest an open heliosphere model as it is shown in Figure 2b (Ahluwalia, 1979). The indicated configuration of the heliosphere requires that the interstellar magnetic field should have a significant component oriented in the manner shown in Figure 2b, with respect to solar dipole. The anomalous features of cosmic-ray intensity during even solar cycles is due to the fact that the given configuration provides a direct access to cosmic-rays in the interstellar space. This model predicts that cosmic-rays are brought in at a fairly low heliolatitude so that diffusion plays a minimum role during the epoch in their transport to the Earth. It follows naturally therefore that during the alternate polar field reversal epochs a closed heliosphere configuration shown in Figure 2a, must be obtainable where the cosmic-rays are incoming from the helioequatorial plane. Diffusion must play a major role in this configuration to transport interstellar cosmic-rays to Earth. Long recovery times are then to be expected during these time periods.

The secondary maximum of the even solar cycles is known that is observed 1–2 years after the solar polar 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 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). On the other hand the hysteresis effect of

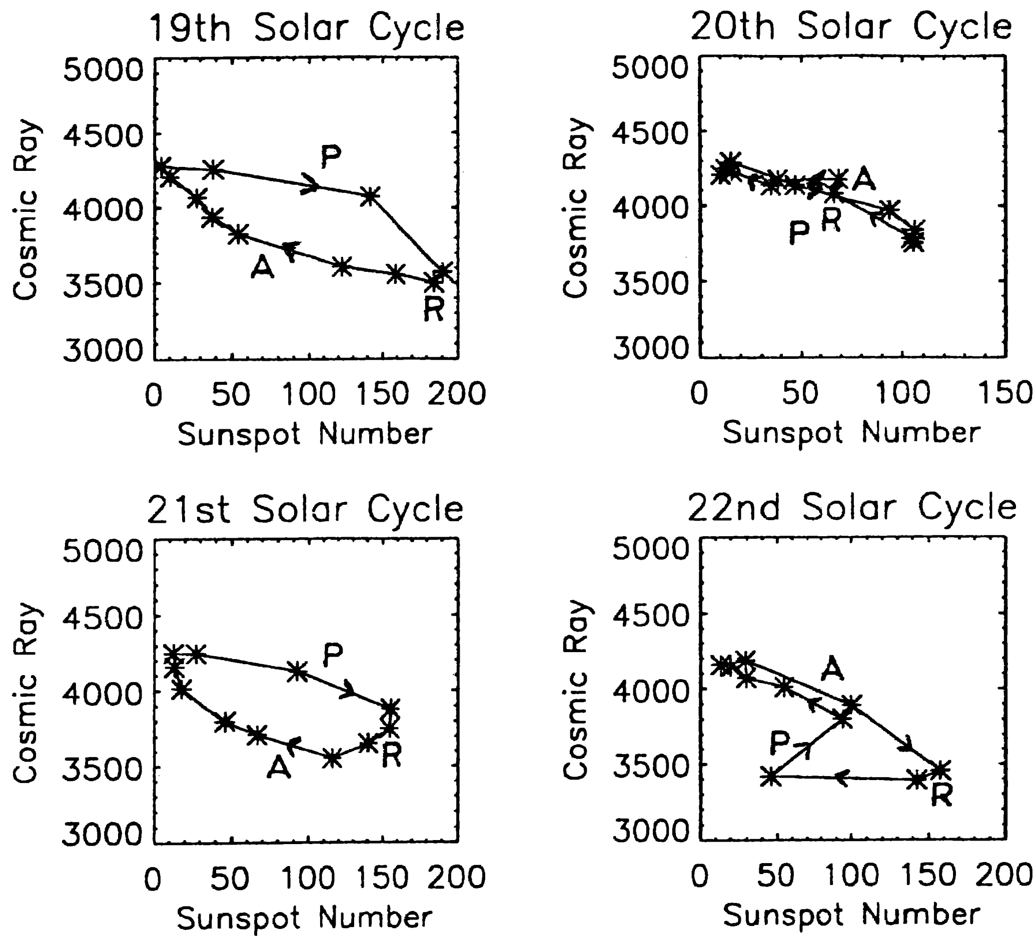

Figure 3. Observed hysteresis curves for the last four solar cycles using Climax Neutron Monitor intensities (P: Parallel, A: Antiparallel, R: Reversal).

cosmic-rays is longer during the odd solar cycles as the route of access becomes longer.

Another complementary feature of the solar cycles with two distinct patterns are the 'pointy' type and the 'mesa' type maxima in cosmic-rays respectively. Jokipii and Thomas (1981) cited its existence in support of their hypothesis that modulation of cosmic-rays is produced by the inclination of the heliospheric neutral current sheet and charged particles drifts. It is known that the current sheet divides the heliosphere into two hemispheres containing oppositely directed magnetic fields. In the half of the solar magnetic cycle where the north polar field is inward, positive particle drift equatorward along the outer boundary of the heliosphere before encountering and drifting inward along the current sheet. During this half, the current sheet tilt is expected to play an important role in the arrival of cosmic-rays in the inner heliosphere. In the other half of the solar cycle positive particles drift indirectly to the inner solar system from the polar regions and then drift outward along the current sheet. During this half cycle the current sheet tilt is less important in determining the cosmic-ray intensity in the inner heliosphere. It has already been noted that this model correctly reproduced the peaked intensity maximum seen in 1965 and 1987 and the flat intensity maximum seen between 1972 and 1977 (Webber and Lockwood, 1988). We are now expected that the flat intensity maximum seen from 1993 up today will be also qualitatively in agreement with the predictions of this model. One should note that the strong correlation between the cosmic-ray intensity and current sheet tilt, leads to the 'driftlike' models which make predictions for different solar magnetic field polarities. However other effects as solar wind speed, number of solar flares, etc. should be equally important in the cosmic-ray modulation process (Marmatsuri *et al.*, 1995).

5. Conclusions

Cosmic-ray data at Neutron Monitor Energies continuously recorded for more than forty years, show an effective 22-year cycle characterizing the long term modulation of galactic charged particles. The differences between even and odd cycles is related to the polarity reversals of the solar magnetic field which occurs around every solar maximum. The interpretation is based on the working hypothesis that when the polar magnetic field of the Sun is nearly parallel to the galactic magnetic field, the galactic cosmic-rays especially those of low rigidities, could intrude more easily into the heliomagnetosphere along the magnetic line of force, as compared with those in the antiparallel state of the magnetic fields.

The results presented in this work point out towards a modulation mechanism during even cycles, where convection plays a more important role than during odd cycles where diffusion dominates. The effect of drifts only determines how the particles gain access to the observation point. In more recent times the effect of gradient drifts in the oppositely directed north and south heliospheric magnetic fields has received a lot ot attention.

Acknowledgements

Thanks are due to the experimental groups of Climax and Inuvik Neutron Monitor Stations and to the director of WDC-A for provided these data.

References

Ahluwalia, H.S.: 1979, *Proc. 19th ICRC* (Paris) **5**, 182.
Ahluwalia, H.S.: 1995, *Proc. 2nd SOLTIP Sym.* **5**, 247.
Babcock, H.W.: 1961, *Astrophys. J.* **133**, 57.
Gnevyshev, M.N.: 1977, *Sol. Phys.* **51**, 175.
Feminella, F. and Storini, M.: 1995, *Proc. 9th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun*, (Florence).

Jokipii, J.R. and Thomas, B.: 1981, *Astrophys. J.* **243**, 1115.
Marmatsouri, L., Vassilaki, A. and Mavromichalaki, H.: 1995, *Adv. Space Res.* **16**, 245.
Mavromichalaki, H., Marmatsouri, E. and Vassilaki, A.: 1988, *Earth, Moon and Planets* **42**, 233.
Nagashima, K. and Morishita, J.: 1980, *Planet. Space Sci.* **28**, 195.
Otaola, J.R., Perez Enriquez, R. and Valdes-Galicia, J.F.: 1985, Proc. 19th ICRC (La Jolla) **4**, 93.
Smart, U.A. and Shea, D.F.: 1981, Adv. Space Res. **1**, 147.
Webber, W.R. and Lockwood, J.A.: 1988, *J. Geophys. Res.* **93**, 8735.
Webber, W.R. and Lockwood, J.A.: 1993, *J. Geophys. Res.* **98**, 21095.