TIME-EVOLUTION OF COSMIC-RAY INTENSITY MODULATION

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Abstract. Application of analyzing time-series into trigonometric series allows the investigation of cosmic-ray intensity variations in a wide periodicity range from a few months to 10 or even more years. By this technique, the amplitude and the phase of all observed fluctuations can be given. For this purpose, cosmic-ray data of five ground-based neutron-monitor stations for the time interval 1964–1985 have been analyzed.

Two kinds of periodicities appeared in these data. The first one includes occurrences at periods greater than two years, as the ones of 10.41, 8.41, and 5.50 yr, which differ very little in amplitude from station to station but are similar in phase, and the second one includes periodicities smaller than two years (24, 12, 8, and 6 months) which are similar in all stations but appeared in variable time intervals.

The possible origin of each observed variation due to a contribution either of cosmic-ray interaction in the upper atmosphere or to the solar dynamics is discussed.

1. Introduction

As is well known, the intensity of galactic cosmic rays is assumed to be essentially constant outside the heliosphere. But the main characteristic of cosmic rays observed inside the solar cavity is the time variability on a wide range of time-scales. The temporal changes observed must be due to the interaction of cosmic-ray particles with the interplanetary magnetic field (IMF) which is carried by the solar wind. So the problem is to find out the pattern of the interplanetary magnetic field and its flow, to determine the time and spatial evolution of their configurations and to relate them to cosmic-ray variations. Unfortunately, the direct measurements of the IMF and the solar-wind plasma are insufficient because they are limited to a region close to the ecliptic plane. On the other hand, cosmic-ray particles provide an indirect measurement of the global structure of the IMF, since they sample a large volume of the solar cavity in their travels from its boundary to the Earth.

Continuous registration of cosmic-ray intensity detecting by IGY detectors and later by Neutron Monitor Stations, extend back to 1937 and now cover almost 4 solar cycles. There is, then, the possibility for a statistical study of long-term variations and periodicities of, say, greater than one year. Most cosmic-ray variational studies include an eleven-year solar cycle variation, Forbush decreases, 27-day variation and the various harmonics of the daily variation.

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Recently, Dorman and Putskin (1981) have proposed that the possible natural large-scale pulsations of the heliosphere are probably the origin of a new type of cosmic-ray variation with characteristic periods varying from 1–2 yr to tens of years.

Attolini, Cecchini, and Galli (1987) applied their statistical technique of cyclograms to the climax neutron monitoring station data and studied the cosmic-ray intensity variations in the periodicity range of 1 to 10 years. The two-year variation in cosmic-rays was observed clearly and not correlated with the sunspot cyclic variations. They had no significant evidence for the existence of a longer period variation.

Okhlopkov, Okhlopkova, and Charakhchyan (1986) have studied the cosmic-ray variations at different isobaric levels and have revealed a new kind of galactic cosmic-ray modulation-zonal modulation. The frequency structure of the cosmic-ray variations has presented significant peaks with periods $T \sim 2$, 1.5, 1, 0.75, and 0.5 yr.

In this paper, we investigate the possibility of detecting cosmic-ray variations at periods greater than 2 yr, as well as other recurrences smaller than 2 yr, by analyzing the time-evolution of the cosmic-ray fluctuations into a network of trigonometric series.

2. Data Analysis

Monthly mean values of five ground-based cosmic-ray stations data have been used for investigating the possible periodicities and their harmonics. These data cover the time interval 1964–1985, since the super neutron monitor stations were in operation. The altitude, the geographic coordinates and the geomagnetic cut-off rigidity of each station are listed in Table I. The cosmic-ray data (corrected for pressure) for each station were normalized during each solar cycle, such as the intensities at solar minimum were taken to be equal to 1.00 and at solar maximum, taken to be equal to zero.

TABLE I

Characteristics of the neutron monitor stations whose data have been utilized in this paper

Station (Super NM-64)	Altitude (m)	Geogr. latitude	Coordinates longitude	Cut-off rigidity (GV)
Alert	57	82.50 N	62.33 W	0.00
Inuvik	21	68.25 N	133.72 W	0.18
Goose Bay	46	53.27 N	60.40 W	0.52
Deep River	145	46.56 N	77.50 W	1.02
Kiel	54	54.30 N	10.10 E	2.29

By applying the method of analyzing time-series into trigonometric series (Xanthakis, 1984) we have investigated the cosmic-ray intensity variations in a wide periodicity range. According to this method, we have first computed the amplitude and the position of the long-term variations expressing them analytically. From the time-series of the observed values I^{obs} of cosmic-ray data, we have subtracted the values which are given by the corresponding analytical expressions (I), respectively. These differences are investigated by power spectral analysis (Blackman and Tuckey, 1959) for possible systematic periodic or quasi-periodic variations. Taking into account the results of the power spectral analysis, we have defined 'graphically' the position and the amplitude of these variations in the time-series of ($I^{obs}-I$) as well as the corresponding width. In this way, we finally express the observed values as a function of these variations, suggesting that those used in these expression parameters would be less than the number of measurements. In this work, the above-mentioned expressions for the five cosmic-ray stations are given in Tables IIa–e, respectively. From these tables, it is concluded that we have a set of long-term periodicities greater than two years and another one of short-term periodicities (given by the symbol W) smaller than two years. The amplitude (a) and the phase (T) of these periodical terms are also given in the above-mentioned tables. A graphic presentation of this analysis is given in the Figures 1(a–e) for the five neutron monitoring stations, respectively. We ought to note from these figures that the observed values of cosmic rays are in very good agreement with the calculated ones when using the above expressions. This last point is also confirmed from the standard deviation between observed and calculated values of cosmic-ray intensity indicated in each of Tables IIa–e. An anomalous behaviour of the cosmic-ray data appears in the Goose Bay station during the year 1978. It is due perhaps to an error of measurements.

A summation of all periods found in this work is listed in Table III. As we can see, the long-term periodicities appear as a small variability from station to station. We can group them into three categories. The first one includes the peaks centred at 10.41 yr, the second one at 8.41 yr and the third one at 5.50 yr. On the other hand, the short-term periodicities (Table III) are similar in all work stations and are independent of the geomagnetic coordinates. This point is confirmed by a power-spectral analysis of cosmic-ray data according to the Blackman and Tuckey method (Blackman and Tuckey, 1959). A typical example of the power spectrum for the Inuvik station is given in Figure 2. Peaks of 22, 14, 6, and 3 months appeared at a significance level of 95%, but peaks of 22 and 14 months are really significant (99%).

3. Discussion of Results

From the above analysis, it is shown that two kinds of periodicities appeared in the cosmic-ray data. The first one includes occurrences at periods greater than 2 years which are a little different in amplitude from station to station but similar in phase, and the second one includes periodicities smaller than 2 years which are similar in all stations but appeared in variable time intervals. This is pointed out in Figure 3 where we have presented all the periodicities (long-term and short-term) for all stations for the time interval 1964–1985. We ought to note that there is a reversal of phase during the year of the solar minimum (1975) which is due to the secondary maximum of cosmic-ray intensity (1972) that characterized the 20th solar cycle as an odd cycle. This reversal has not appeared in the 21st solar cycle which is an even cycle (Otaola, Perez-Enriquez, and Valdes Galicia, 1985; Mavromichalaki, Marmatsouri, and Vassilaki, 1988).

TABLE IIa

Analytical expressions of cosmic-ray intensity as a function of periodicities for the Alert station ($\sigma = \pm 0.033$, freedom of degree = 149)

$$I^{\text{cal}} = 0.588 + 0.400 \sin \frac{2\pi}{114} (T\text{-1962III}) + 0.350 \sin \frac{2\pi}{72} (T\text{-1971IX}) + 0.400 \sin \frac{2\pi}{120} (T\text{-1975I}) + W$$

1962III–71IX 1971IX–74VII 1975I–85XII

$$W = a_1 \sin \frac{2\pi}{24} T + a_2 \sin \frac{2\pi}{12} T + a_3 \sin \frac{2\pi}{8} T + a_4 \sin \frac{2\pi}{6} T$$

a_1	T
+0.100	1967IX–68IX
−0.150	1970III–71III, 1972VII–73VII
+0.150	1974XI–75XI, 1976III–77III
−0.200	1978XII–79XII

a_2	T
+0.150	1965IX–66III, 1981V–81XI
+0.100	1966I–66VII, 1973XII–74VI, 1979XII–80VI
−0.100	1970III–70IX, 1971I–71VIII, 1973I–73VII
−0.200	1973III–73IX
−0.050	1976VII–77I
−0.070	1977IV–77X
−0.250	1978II–78VIII
+0.300	1981X–82IV
−0.150	1982VI–82XII
+0.200	1983VIII–84II

a_3	T
+0.100	1968XII–69IV
−0.150	1969IV–69VIII
+0.200	1975XII–76IV, 1983I–83V
−0.100	1980IX–81I
+0.300	1982II–82VI
+0.150	1983V–83IX, 1983XII–84IV
+0.070	1978XII–79IV

a_4	T
−0.100	1966VIII–66XII, 1972VII–72X
+0.100	1967II–67V, 1984V–84VIII
+0.070	1967VI–67IX, 1972II–72VIII, 1978II–78V, 1978
−0.150	1968X–69I
+0.150	1971X–72I
+0.050	1977X–78I, 1980XII–81VI

The symbol W gives the short-term periodicities which are smaller than two years. The amplitude (a) and the period (T) of the periodical terms are also given analytically. The roman letters express the months where we have periodic or quasi-periodic variations.

TABLE IIb

Analytical expressions of cosmic-ray intensity as a function of periodicities for the Inuvik station ($\sigma = \pm 0.028$, freedom of degree = 134)

$$I^{\text{cal}} = 0.565 + 0.400 \sin \frac{2\pi}{96} (T\text{-}1963\text{I}) + 0.250 \sin \frac{2\pi}{80} (T\text{-}1971\text{I}) + 0.400 \sin \frac{2\pi}{128} (T\text{-}1974\text{V}) + W$$

1963I–71I 1971I–74V 1974V–1985II

$$W = a_1 \sin \frac{2\pi}{24} T + a_2 \sin \frac{2\pi}{12} T + a_3 \sin \frac{2\pi}{8} T + a_4 \sin \frac{2\pi}{6} T$$

a_1	T
+ 0.150	1967VI–68VI
− 0.150	1969II–70XII
− 0.100	1972V–73V
+ 0.200	1974X–75X, 1981V–82V, 1983IV–84IV

a_2	T
− 0.100	1964III–64IX
− 0.050	1966II–66VIII
+ 0.080	1969VI–69XII
− 0.200	1972XI–73V
+ 0.050	1975VII–76II, 1976V–76XI
+ 0.350	1982II–82VIII
− 0.150	1979V–80V

a_3	T
− 0.080	1966III–65XI, 1979III–79VII
+ 0.080	1973IX–74V, 1975VII–75XI
− 0.050	1977V–771X
+ 0.050	1977IX–78IX, 1978X–79II, 1978XI–79III
− 0.150	1978IV–78VII

a_4	T
− 0.080	1966IX–66XII, 1969II–69V, 1970XI–71II, 1982X–83I
− 0.050	1967I–67IV
+ 0.100	1968IV–68X
− 0.150	1970II–70V, 1981IX–81XII

a_5	T
− 0.100	1972II–72V, 1984IV–84VII
+ 0.050	1973II–73V
+ 0.080	1980VI–81I
− 0.250	1982V–82VIII
+ 0.150	1983II–83V

The symbol W gives the short-term periodicities which are smaller than two years. The amplitude (a) and the period (T) of the periodical terms are also given analytically. The roman letters express the months where we have periodic or quasi-periodic variations.

TABLE IIc

Analytical expressions of cosmic-ray intensity as a function of periodicities for the Goose-Bay station ($\sigma = \pm 0.030$, freedom of degree = 111)

$$I^{\mathrm{cal}} = 0.420 + \underset{1963\mathrm{V}-71\mathrm{V}}{0.400 \sin \frac{2\pi}{96} (T\text{-}1963\mathrm{V})} + \underset{1971\mathrm{V}-74\mathrm{VII}}{0.250 \sin \frac{2\pi}{80} (T\text{-}1971\mathrm{V})} +$$

$$+ \underset{1974\mathrm{III}-84\mathrm{III}}{300 \sin \frac{2\pi}{130} (T\text{-}1974\mathrm{III})} + 0.600 \sin \frac{2}{130} (T\text{-}1984\mathrm{XII}) + W$$

$$W = a_1 \sin \frac{2\pi}{24} T + a_2 \sin \frac{2\pi}{12} T + a_3 \sin \frac{2\pi}{8} T + a_4 \sin \frac{2\pi}{6} T$$

a_1	T
+ 0.150	1967XI–68XI, 1978XII–79XII
− 0.150	1972IX–74IX
− 0.100	1975VII–76VII, 1984II–85II

a_2	T
+ 0.100	1965I–65VII, 1965IX–66III, 1981XI–82V
+ 0.080	1967VI–67XII, 1978VII–791
+ 0.150	1968XII–69VI
− 0.100	1969II–70II, 1974II–74VII, 1977V–77XI, 1984II–84VIII
− 0.150	1970VIII–71II, 1974IV–74X, 1982VI–82XII
− 0.080	1970XII–71XII

a_3	T
− 0.200	1970V–70IX
− 0.100	1980IX–81I
+ 0.080	1981VI–81X, 1981II–82VI
− 0.080	1985X–86I

a_4	T
− 0.050	1965XII–66VI, 1971XII–72III, 1975X–76IV, 1979IV–79X, 1983–84I, 1986VII–86X
− 0.150	1966XII–67II, 1972VII–72X, 1973III–73VI
− 0.080	1968II–68V, 1968V–68VIII, 1968X–69I, 1985VI–85IX, 1986X–87I
+ 0.080	1969XII–70VI
− 0.100	1972V–72VIII, 1981III–81VI, 1982XI–83II, 1986I–86IV
− 0.050	1982IV–82VII

The symbol W gives the short-term periodicities which are smaller than two years. The amplitude (a) and the period (T) of the periodical terms are also given analytically. The roman letters express the months where we have periodic or quasi-periodic variations.

TABLE IId

Analytical expressions of cosmic-ray intensity as a function of periodicities for the Deep River station ($\sigma = \pm 0.033$, freedom of degree = 154)

$$I^{\text{cal}} = 0.606 + 0.400 \sin \frac{2\pi}{104} (T\text{-}1962\text{IX}) + 0.350 \sin \frac{2\pi}{72} (T\text{-}1971\text{V}) + 0.400 \sin \frac{2\pi}{125} (T\text{-}1974\text{X}) + W$$

1962IX–1971V 1971V–1974V 1974X–1985III

$$W = a_1 \sin \frac{2\pi}{24} T + a_2 \sin \frac{2\pi}{12} T + a_3 \sin \frac{2\pi}{8} T + a_4 \sin \frac{2\pi}{6} T$$

a_1	T
−0.300	1970III–71III
−0.150	1972V–73V
+0.200	1973VIII–74VIII
+0.150	1974XI–75XI
−0.200	1977XI–78XI
−0.250	1978XII–79XII
+0.050	1985VIII–86VIII
+0.250	1983VI–84VI
+0.100	1984XI–85XI

a_2	T
−0.100	1965V–66V, 1971XI–72V, 1972IV–72X, 1977V–77
+0.100	1981VI–81XII, 1986VII–87I
+0.150	1967XII–68VI
−0.250	1973III–73IX
−0.300	1980VII–81I
+0.200	1983I–83VII

a_3	T
+0.090	1968XI–69IV, 1982V–82VIII
−0.200	1969IV–69VIII
+0.150	1970VI–70XI
+0.050	1970X–71II
−0.100	1974IV–74VIII
−0.050	1978IX–79I
+0.200	1981XI–82III

a_4	T
+0.050	1967V–67IX, 1978I–78IV
−0.150	1968X–69I, 1979VII–79X, 1984II–84V
−0.100	1973III–73VI, 1978IV–78X, 1980V–80VII, 1980VII–81I, 1981III–81VI
−0.50	1981II–81IV
−0.300	1982V–82VIII
+0.100	1983VI–83IX
−0.100	1986I–86VII

The symbol W gives the short-term periodicities which are smaller than two years. The amplitude (a) and the period (T) of the periodical terms are also given analytically. The roman letters express the months where we have periodic or quasi-periodic variations.

TABLE IIe

Analytical expressions of cosmic-ray intensity as a function of periodicities for the Kiel station ($\sigma = \pm 0.024$, freedom of degree = 115)

$$I^{\mathrm{cal}} = 0.582 + 0.400 \sin \frac{2\pi}{26} (T\text{-1963III}) + 0.250 \sin \frac{2\pi}{86} (T\text{-1971III}) + 0.400 \sin \frac{2\pi}{120} (T\text{-1974XI}) + W$$

1963III–71V 1971III–74III 1974XI–85XII

$$W = a_1 \sin \frac{2\pi}{24} T + a_2 \sin \frac{2\pi}{12} T + a_3 \sin \frac{2\pi}{8} T + a_4 \sin \frac{2\pi}{6} T$$

a_1	T
−0.050	1985I–86I
−0.150	1970IV–73V
−0.100	1972V–73V
+0.150	1975XII–76XII
+0.200	1983VII–84VII

a_2	T
−0.100	1965V–65XI, 1972XII–73V
−0.080	1966V–66XI
+0.100	1967VIII–68II, 1967XII–68VI, 1973XI–74XI
−0.050	1970XII–71IV, 1974V–74XI
−0.200	1978II–78VIII
−0.150	1979V–80V
+0.150	1981V–81XI, 1983I–83VII
+0.250	1981X–82IV

a_3	T
−0.050	1964XII–65IV
−0.080	1966II–66VI, 1966XII–67IV
+0.100	1968VI–68X, 1968XII–67IV
−0.150	1969IV–69VIII
−0.200	1970IV–70VII
+0.080	1975XII–76IV
−0.100	1979II–79X

a_4	T
−0.150	1966VIII–66XI
+0.100	1968III–68VI
−0.100	1968X–69I, 1970IV–70IX
+0.050	1971VI–71VIII, 1976VIII–76XI, 1980VII–81I, 1982VI–82IX, 1985X–86I
−0.080	1971III–71VI, 1977VII–77X, 1979XII–78III
+0.080	1975V–75XI, 1975VII–75XI, 1982IX–82XII
+0.150	1976X–77I
−0.050	1984X–851

The symbol W gives the short-term periodicities which are smaller than two years. The amplitude (a) and the period (T) of the periodical terms are also given analytically. The roman letters express the months where we have periodic or quasi-periodic variations.

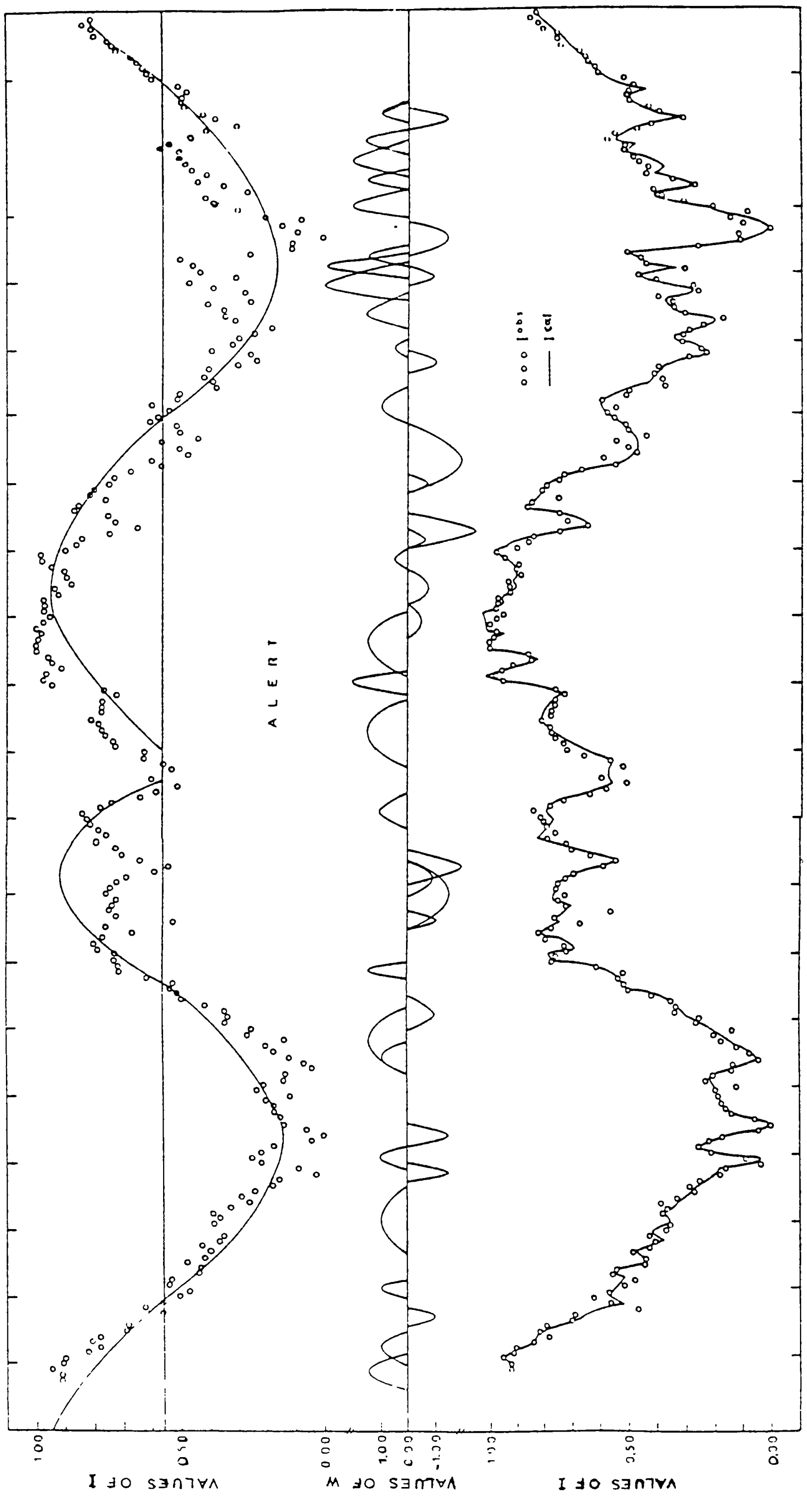
VALUES OF I
VALUES OF W
VALUES OF I
ALERT
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Fig. 1a.

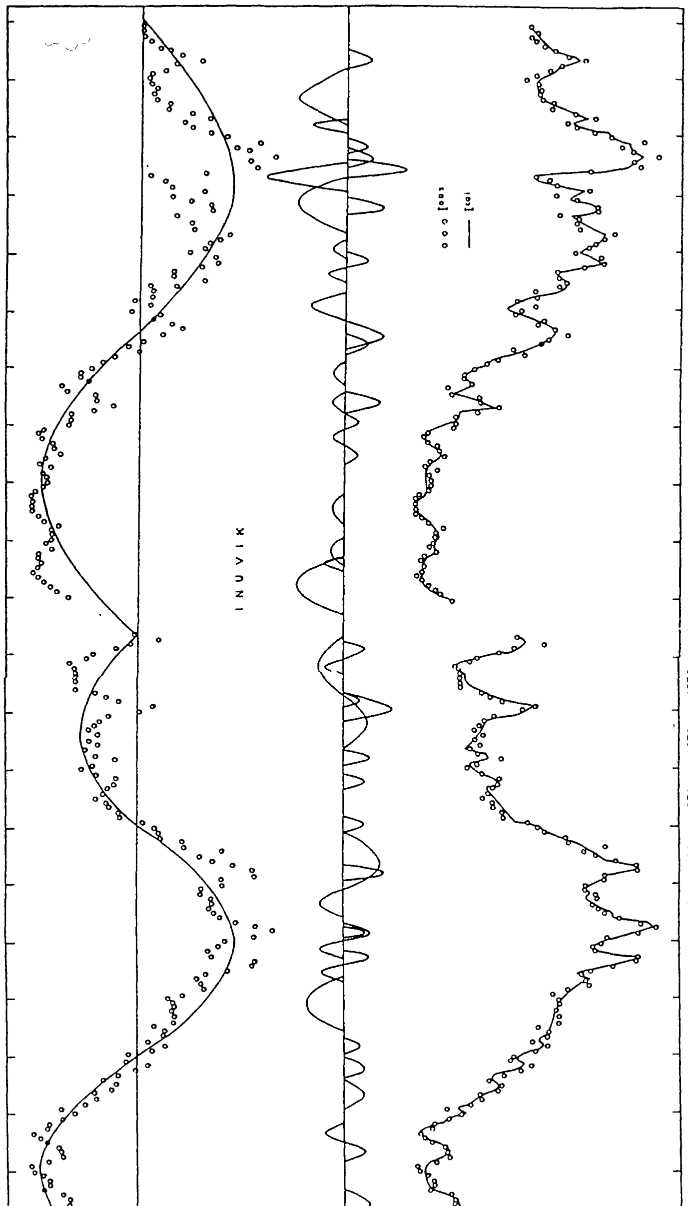
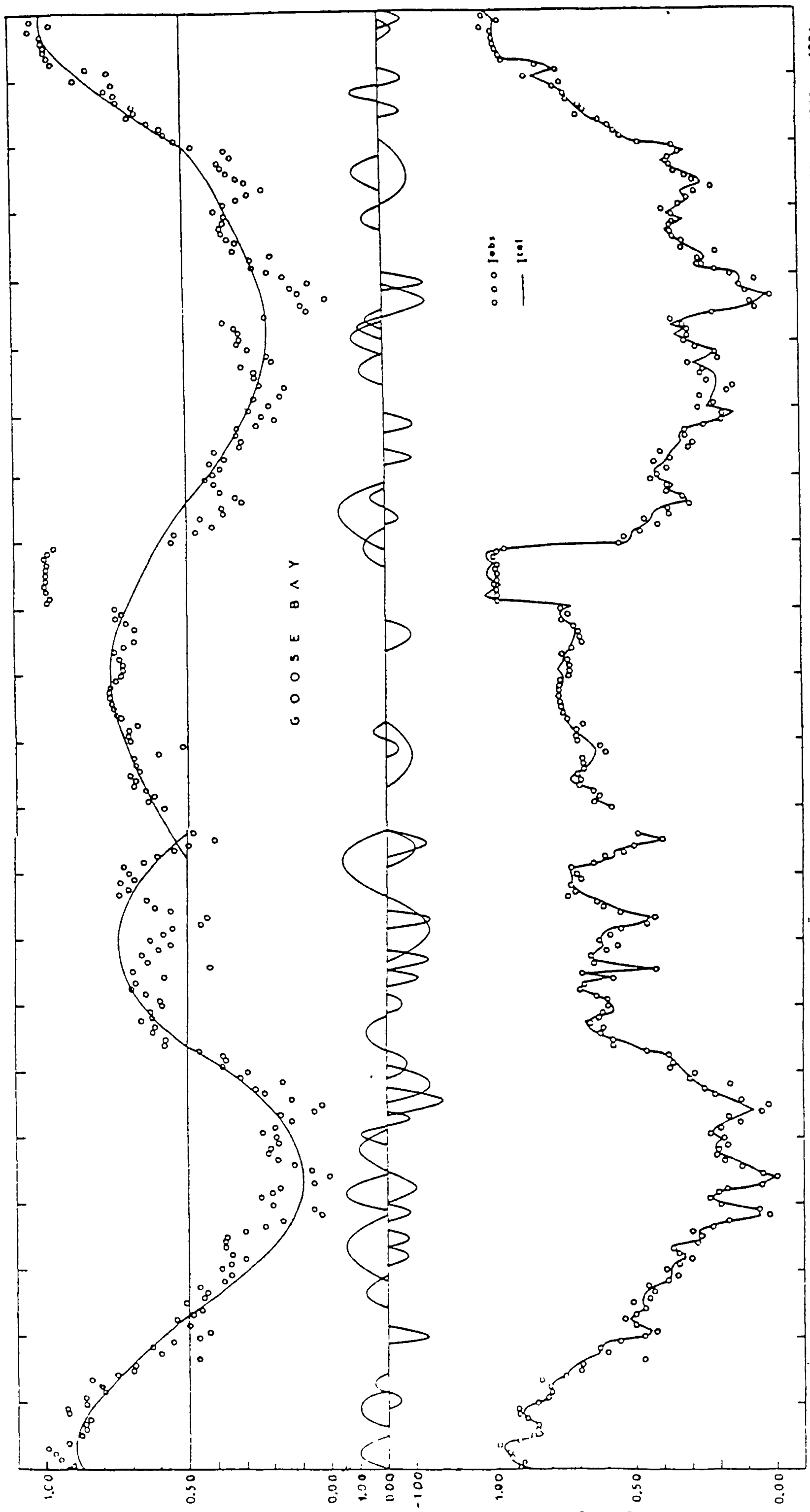


Fig. 1b.


GOOSE BAY
o o o Iobs
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YEARS
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1972
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1981
1982
1983
1984
1985
1986
VALUES OF I
VALUES OF W
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1.00
0.50
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1.00
0.00
-1.00
1.00
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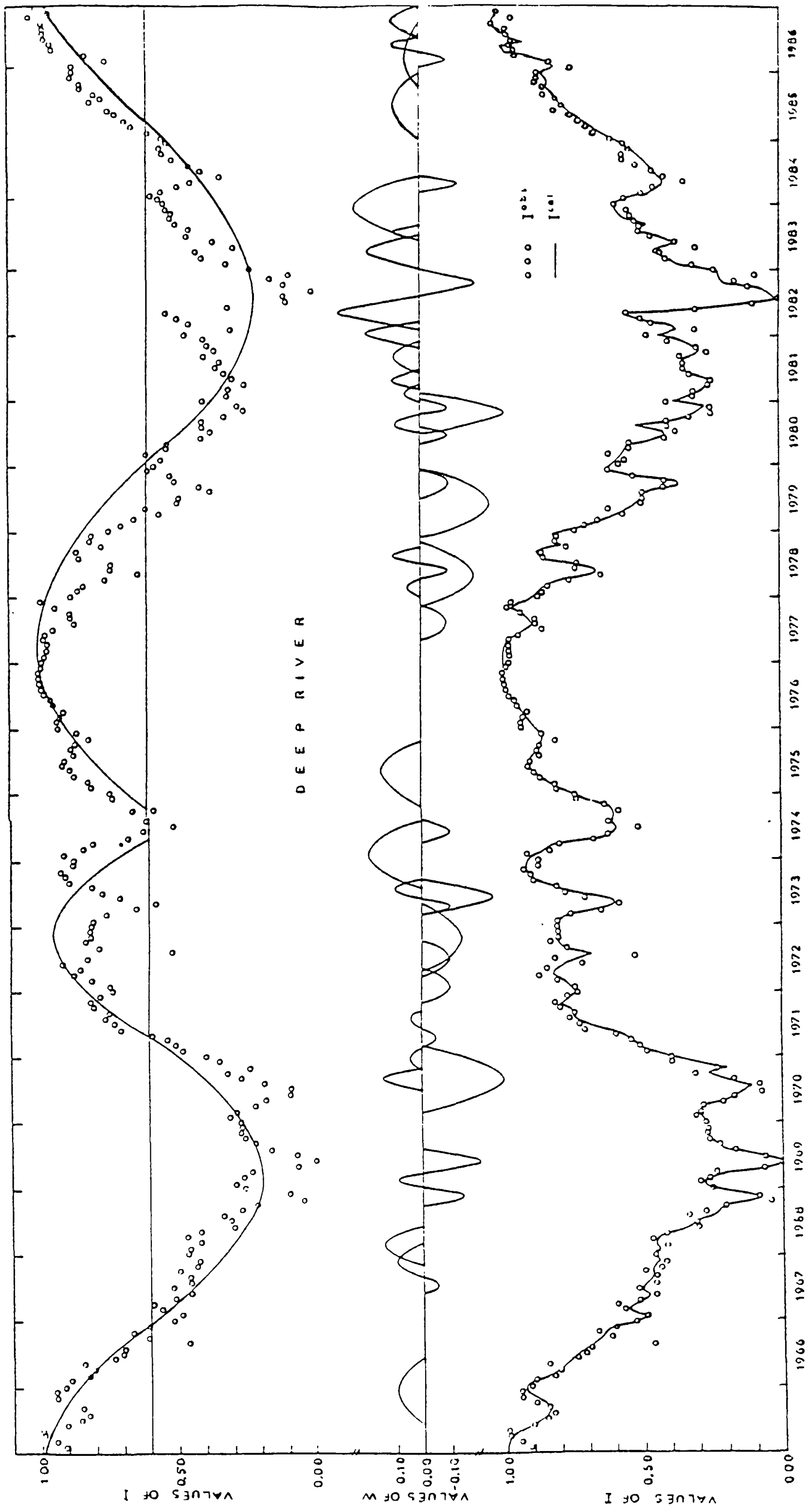
0.00

Fig. 1c.


DEEP RIVER
YEARS
VALUES OF I
VALUES OF W
VALUES OF I
1966
1967
1968
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1971
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1973
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1982
1983
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1985
1986
1.00
0.50
0.00
0.10
0.00
-0.10
1.00
0.50
0.00

Fig. 1d.

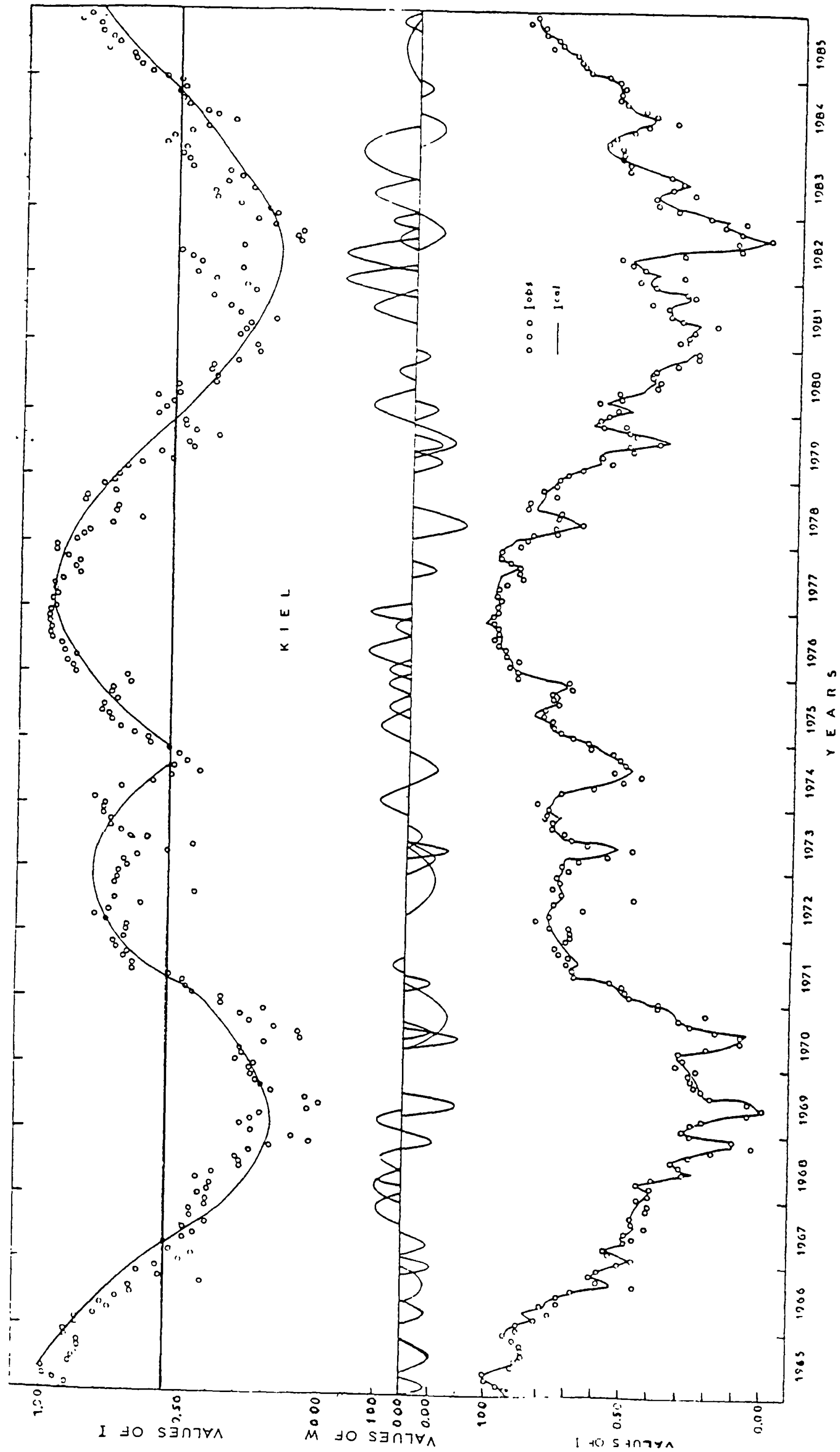

Fig. 1e.

Fig. 1a–e. Graphic presentation of the cosmic ray intensity for the (a) Alert, (b) Inuvik, (c) Goose Bay, (d) Deep River, and (e) Kiel stations, respectively. The upper panel gives the long-term periodicities and the middle one gives the short-term periodicities. The lower panel gives the observed (circle points) and calculated (continuous line) by the expressions of the Tables IIa–e values of cosmic-ray intensity, respectively.

TABLE III

A synoptic table of the periodicities observed in neutron monitor data

Station	Long-term periods (months)			Short-term periods (months)			
Alert	120	72	114	24	12	8	6
Inuvik	128	80	96	24	12	8	6
Goose Bay	130	80	96	24	12	8	6
Deep River	125	72	104	24	12	8	6
Kiel	120	86	96	24	12	8	6

3.1. Long-term periodicities

The long-term periodic behaviour of cosmic-ray intensity consists of three groups centered on 10.41, 8.41, and 5.50 yr.

The first group of periods is the well-known variation of 11 yr mentioned several times in the data and on the evidence available from the sunspot numbers. This variation seems to be significant in any description of the solar cycle. In our analysis, this period seems to vary from 118 to 130 months for the neutron monitoring stations examined here.

Cole (1973) suggested that the free-running length of the solar cycle is 11.8 years, but that it is triggered every 10.45 yr. The amplitude is modulated by a seasonal periodicity of 11.9 yr. Recently, Attolini, Cecchini, and Galli (1987) using the cosmic-ray data of Huancayo (1937–1953) and Climax (1953–1979) stations and searching for an overall correlation of the sunspot number (R_z) as an index of solar activity with the cosmic-ray intensity, have found that the coherency appears to be higher for the peaks of the higher harmonics of the fundamental frequency 10.67 yr (1.77, 1.58, 1.33, 1.18). They have also noted that it is important to distinguish between variations that are strictly related to sunspot activity from cosmic-ray variations which are related to other types of solar activity with an 11-yr period that might appear with a different spectrum in the higher harmonics.

As far as the second group of periods with a mean value of 8.41 yr is concerned, Cole (1973), from a power spectrum analysis of the 22-yr cycle, found a significant peak near the 7.75 yr period by considering the polarity of the solar magnetic field. It is significant that the group of these peaks is similar in structure to the group of peaks associated with the 22-yr cycle.

Finally, the third group of peaks near the 5.50 yr cycle can be related to the 11-yr cycle as Cole (1973) has already shown. From his power spectrum analysis of the relative sunspot number from 1700 until 1969, it is pointed out that there is a group of peaks around the 5.75-yr period. Attolini, Cecchini, and Galli (1985) have also found the coherence between cosmic-ray intensity and sunspot number shows a significant value at the peak of the 4.74 yr period. Concerning this variation, we can say that it might be a signature of a true effect, but it is not the second harmonic of the 11-yr cycle as in the sunspot number, since it does not appear in the coherency spectrum.

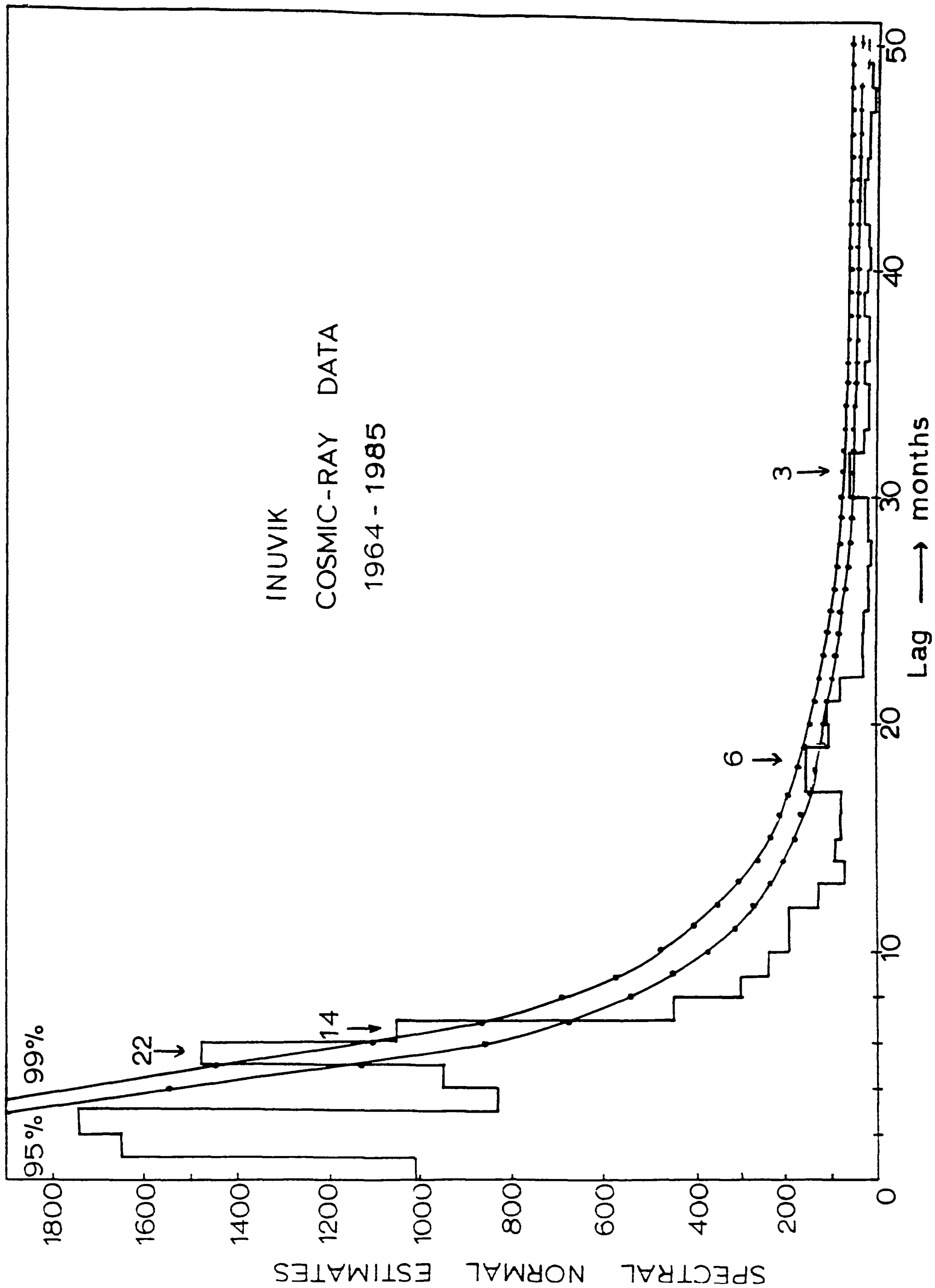

Fig. 2. A typical example of the power spectrum analysis for the Inuvik station.

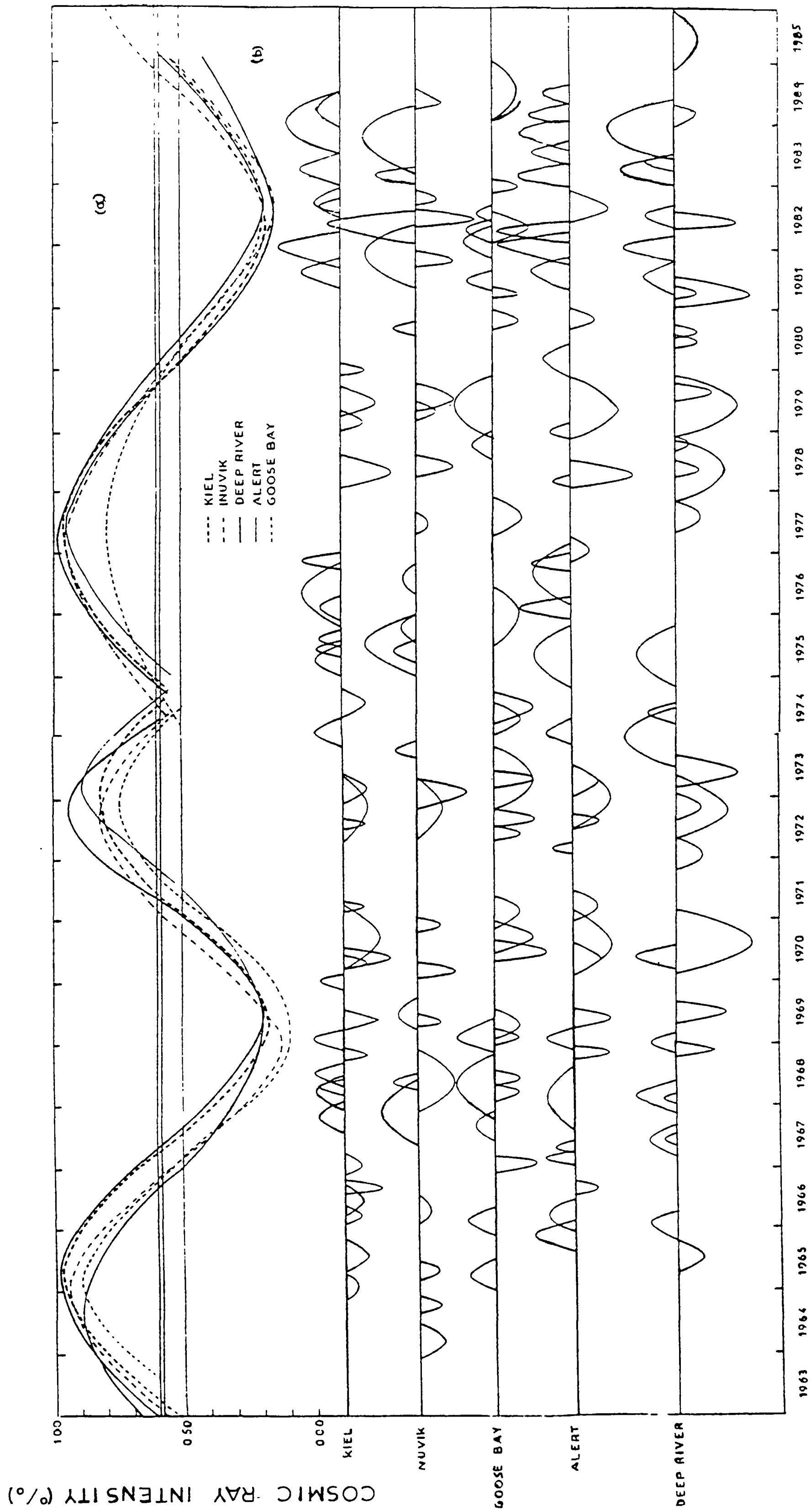

Fig. 3. Long-term and short-term periodicities for all examined neutron monitor stations.

Dorman and Putskin (1981) have proposed that it is very probable that so long period variations in the cosmic-ray intensity, as these of the 10.41, 8.40, and 5.50 yr, are determined by the dynamics of the solar cavity. However, due to a lack of knowledge of the position and behaviour of the heliosphere boundary, the estimate of the proper pulsation periods of the cavity can range from 2–3 yr to 10, or even more. On the other hand, the length of the cosmic-ray data record (only two solar cycles) is insufficient to fully explore the resonance pulsation range.

3.2. Short-term periodicities

The short-term periodicities which have been found in the cosmic-ray data in this work, are of the order of 24, 12, 8, and 6 months.

A significant variation with a period around 2 yr has been revealed by the study of the cosmic-ray power spectrum by Attolini *et al.* (1985a). This cannot be explained as a high order harmonic of the 11-yr solar cycle. They have proposed that the origin of this intensity change has to be found in a geomagnetic effect correlated to the solar activity. However, the connection is not completely clear and its origin as a resonance effect to heliosphere pulsation cannot be ruled out, especially if we notice that the oscillations are dumped out with the 22-yr cycle.

Sugiura and Poros (1977) have shown the existence of highly correlated quasi-biennial variations in the geomagnetic field and in the solar activity expressed by the sunspot number or by the Ottawa 10.7 solar flux. They have shown that there is the possibility that the 2-yr variation in the cosmic-ray intensity is connected to the 2-yr variation in solar activity via the geomagnetic effect. This last point can be confirmed by the fact that the variation seems to change with the asymptotic longitude, as found by Charakhchyan, Okhlopkov, and Okhlopkova (1979a, b). The dependence on the polarity of the interplanetary medium with respect to the geomagnetic field, can play an important role.

Examining the zonal modulation of the charged component of cosmic-rays in the lower atmosphere in terms of sounding measurements, have also been found the 2-yr and 1-yr variations which are different in amplitude from station to station.

The 2-yr variation has also been identified in neutron monitor data by Kolomeets, Mukhanov, and Shvartsman (1973) and atmospheric sounding data by Okhlopkov, Okhlopkova, and Charakhchyan (1979, 1986). The 2-yr periodicity has also been found in a number of high speed solar wind streams (Xanthakis, Poulakos, and Petropoulos, 1988), as also in the neutrino flux (Sakurai, 1981) measured by Davis, Evans, and Cleveland (1978).

The 1-yr periodicity has also been identified in neutron monitor data by Kolomeets, Mukhanov, and Shvartsman (1973) and Attolini, Cecchini, and Galli (1987). Okhlopkov, Okhlopkova, and Charakhchyan (1986) also found the annual cosmic-ray variation in the lower atmosphere on the basis of cosmic-ray measurements on sounding balloons. They have also found periods of 9 and 6 months, which can be related to the 8- and 6-month periodicities of the cosmic-ray data found in the present work. We ought also to note that the number of high-speed solar wind streams present 8, 6, and 4 months variations (Xanthakis, Poulakos, and Petropoulos, 1988).

4. Conclusions

From the analysis of cosmic-ray intensity records in the 20th and 21st solar cycles using the method of analyzing into trigonometric series and the method of power spectrum analysis, we can draw the following conclusions:

Cosmic-ray intensities exhibit different time evolutions in the 20th and 21st solar cycles. It is apparent from Figure 3 that the cosmic-ray intensity appears as a secondary peak during the declining phase of the 20th cycle, while the 21st cycle was characterized by one peak. So the change of phase which appeared during the year 1975, is just what one would expect from a drift model incorporating a wavy neutral sheet with the title angle varying from small to large angles as solar activity increases (Kota and Jokipii, 1983).

On the other hand, it is very important to distinguish between variations that are strictly related to sunspot activity, as it is the 11-yr variation from cosmic-ray variation related to other types of solar activity.

Concerning the 8.40 and 5.50 yr pulsations, care should be taken in the interpretation. It might be a signature of a true effect in the solar activity (Cole, 1973) or it is determined by the dynamics of the solar cavity as Dorman and Putskin (1981) have predicted. The last point is much more reliable because the high-speed solar wind streams show the same periodic behaviour as the cosmic-ray data.

The subject of biennial variation also deserves attention. According to Charakhchyan *et al.* (1985), the 2-yr variation seen earlier in stratosphere measurements is not only a geophysical effect but can be clearly observed in satellite data, too. Cosmic-ray fluxes were shown to be in a quite sharp anti-phase with the geomagnetic A_p-index, suggesting that a relatively local effect is responsible for the biannual variation of cosmic-rays. Though the magnitude of this variation undergoes considerable changes, a closer look seems to rule out a close connection with solar activity via a geomagnetic effect. The interpretation of this phenomenon is still an open question.

The annual variation of cosmic-ray flux found by the power spectrum analysis seems to have a shift from 12 to 14 months as was also observed by Attolini, Cecchini, and Galli (1987). It means that there is a contamination of the influence of the solar coronal holes on cosmic-ray intensity variations and on the dependence of the annual variation, due to the asymmetry of the solar activity itself.

Finally, the short-term periods of 8 and 6 months, and perhaps 3 months, appeared for the first time in ground-based cosmic-ray intensities, but they have also been observed by sounding balloons. These periods have been also found in solar wind streams.

In this work, we give for the first time the amplitude and the phase of all observed periodicities in the cosmic-ray data which present one differing structure variation as a function of the time for every geographic latitude. This could be attributed to the anisotropies of the cosmic-ray intensity closely related to the local gradients, sidereal anisotropies and solar induced anisotropies (Kota, 1985). In the future, the study of cosmic-ray periodicities with other neutron monitor stations during more than two solar cycles cosmic-ray records, will lead us to have a better understanding of the origin of each observed variation, which is useful for the search of interplanetary physical conditions.

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References

Attolini, M.R., Cecchini, S., and Galli, M.: 1985, *Proc. 19th Int. Cosmic Ray Conf. (La Jolla)* **5**, 67.
Attolini, M. R., Cecchini, S., and Galli, M.: 1987, *Astrophys. Space Sci.* **134**, 103.
Attolini, M. R., Cecchini, S., Castagnoli, G. and Galli, M.: 1985, *Proc. 19th Int. Cosmic Ray Conf. (La Jolla)* **5**, 71.
Blackman, R. B. and Tuckey, J. W.: 1959, *The Measurement of Power Spectra*, Dover, New York.
Charakhchyan, T. N., Okhlopkov, V. P., and Okhlopkova, L. S.: 1979a, *Proc. 16th Int. Cosmic Ray Conf. (Kyoto)* **3**, 297.
Charakhchyan, T. N., Okhlopkov, V. P., and Okhlopkova, L. S.: 1979b, *Proc. 16th Int. Cosmic Ray Conf. (Kyoto)* **3**, 308.
Charakhchyan, T. N., Gorchakov, E. V., Okhlopkov, V. P., Okhlopkova, L. S., and Tenovskaya, M. V.: 1985, *Proc. 19th Int. Cosmic Ray Conf. (La Jolla)* **5**, 90.
Cole, T. W.: 1973, *Solar Phys.* **30**, 103.
Davis, R., Jr., Evans, J. C., and Cleveland, B. I.: 1978 in E. C. Flower (ed.), *The Solar Neutrino Problem*, Neutrino Purdue Univ. Lafayette, No. 78, p. 53.
Dorman, L. I. and Putskin, V. S.: 1981, *Astrophys. Space Sci.* **79**, 397.
Kota, J.: 1985, *Proc. 19th Int. Cosmic Ray Conf. (La Jolla)* **9**, 275.
Kota, J. and Jokipii, J. P.: 1983, *Astrophys. J.* **265**, 573.
Kolomeets, E.V., Mukhanov, I. V., and Shvartsman, Ya. E.: 1973, *Proc. 13th Int. Cosmic Ray Conf. (Denver)* **3**, 1207.
Mavromichalaki, H. Marmatsouri, E., and Vassilaki, A.: 1988, *Earth, Moon and Planets* **42**, 233.
Okhlopkov, V. P., Okhlopkova, L. S., and Charakhchyan, T. N.: 1979, *Geomagnetizm i Aeronomiya* **19**, 287.
Okhlopkov, V. P., Okhlopkova, L. S., and Charakhchyan, T. N.: 1986, *Geomagnetizm i Aeronomiya* **26**, 19.
Otaola, J. A., Perez-Enriquez, R., and Valdes Galicia, J. F.: 1985, *Proc. 19th Int. Cosmic Ray Conf. (La Jolla)* **4**, 93.
Sakurai, Kunimito: 1981, *Solar Phys.* **74**, 38.
Sugiura, H. and Poros, D. J.: 1977, *J. Geophys. Res.* **82**, 5621.
Xanthakis, J.: 1984, *Tectonophysics* **107**, 173.
Xanthakis, J., Poulakos, C., and Petropoulos, B.: 1988, *Astrophys. Space Sci.* **141**, 233.