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Power spectra of cosmic ray intensity for years of solar activity minimum and maximum

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Abstract. The cosmic ray power spectra in the low-frequency range (2.3 x 10^{-8} Hz to 5.8 x 10^{-6} Hz; periodicities from 2 to 500 days) during the epoch 1964-1995 was carried out over a wide range of particle rigidities. Our spectral analysis for the periods of solar activity maximum and minimum displayed different behaviors. The spectral density of cosmic rays showed peaks of varying amplitude with the solar rotation period and its harmonics due to the different mean rigidity response. Spectral power is high for solar activity cycles 20th and 22nd. Also, the first three harmonics of the solar rotation period (27-, 13.5- and 9-days) are well defined for even cycles. There is higher power density during qA<0 epoch than during qA>0 epoch.

1. Introduction

Several authors had studied the frequency distribution of the cosmic ray intensity (CRI) scintillations in the low frequency range 10^{-7} to 10^{-4} Hz (e.g., Owens and Jokipii, 1972; 1974; Jokipii and Owens, 1976; Attolini et al., 1977; 1984; Bishara and El-Borie, 1990a). They had related the power spectral density (PSD) of the CR flux to fluctuations in the interplanetary magnetic field (IMF) throughout their propagation to the Earth. The low frequency power spectra of CRIs could be understood quantitatively as being induced by the random fluctuations in the IMF. Also, fluctuations in the solar wind and interplanetary parameters were examined (El-Borie et al., 1997a; 1997b) to give us valuable information about the CRs and IMF. Between the low frequency (the 11- year of CR variation) and high frequency (the diurnal variation), there exist a wide range of CRI variations. The neutron monitors (NMs), especially at low rigidities recorded lower CRIs during the 1954/1976 solar minimum activity periods in comparison with similar conditions in 1965/1987 and the observed differences of spectra between them were significantly large (Moraal et al., 1989; Reinecke and Potgieter, 1994). Belov et al. (1993) concluded that the 1954/1976 spectra are softer than in 1965/1987. Bazilevskaya et al. (1993) reported that at the low cutoff rigidity, the peak intensities for the 1965, 1976, and 1987 years were almost the same but at medium rigidity the peak was significantly lower in 1976 than in 1965/1987.

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We present a study of CRIs power spectra, particularly their spectral characteristics in various frequency domains (2.3 x 10^{-8} Hz to 5.8 x 10^{-6} Hz), at low and high energies particle during consecutive solar minimum and maximum epochs from 1964 to 1995.

2. Data and analysis

We have used the daily average cosmic-ray counting rates observed with the NMs at Deep River (DR), Huancayo (HUN), and Mt. Wellington (WEL), surface vertical pointing muon telescope (SMT) at Nagoya (NAG), as well as the underground north pointing muon telescopes at Mawson (MAW UG).The median primary rigidity R_m of their response lies in the range, 16 GV ≤ R_m ≤ 165 GV, while their geomagnetic vertical cutoff rigidity R_o covers the range 1.02 GV ≤ R_o ≤ 13.45 GV. A series of power spectral density analysis (PSD) have been performed on daily averages of the CRI for minimum (1964-65, 1975-76, 1985-86 and 1994-95) and maximum (1968-69, 1979-80 and 1989-90) solar activity epochs. Significant gaps in data have been considered (Fahlman and Ulrych, 1982). Days of large ground level enhancements caused by solar flares were eliminated. Yearly linear trends were performed to compensate for instrumental variations. Fourier transformations were then used to yield the power spectral density (PSD) and the results were smoothed using the Hanning Window function.

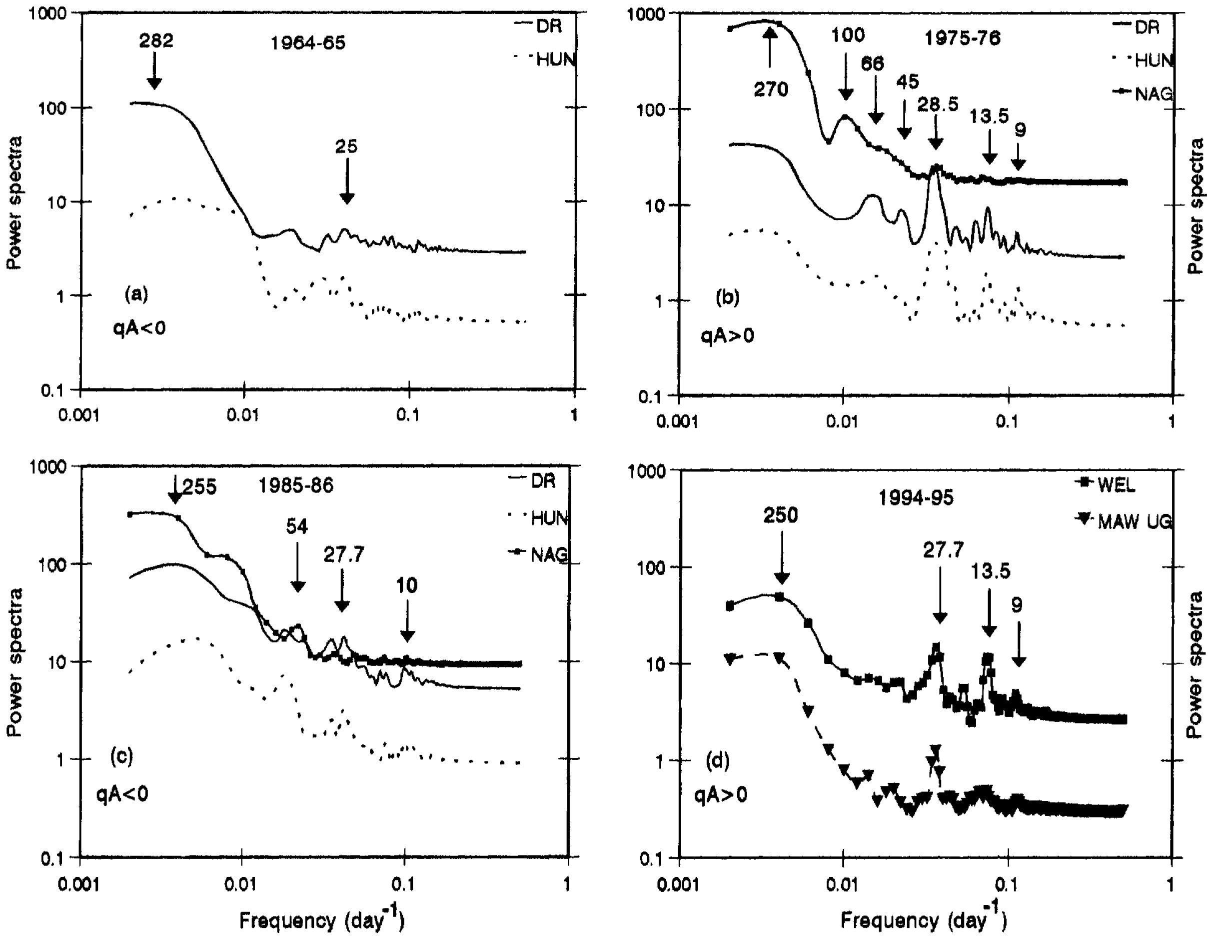

Fig. 1. The PSD of 1 day averages of the CRI observed at DR, HUN, WEL, NAG, and MAW UG over four consecutive solar activity years (1964-65, 1975-76, 1985-86, and 1994-95). The solar magnetic polarity state (qA>0 or qA<0) is shown.

3. Results and discussion

Figure 1 (panels a to d) displays the PSD of daily averages of galactic CRIs for the four consecutive minimum periods (1964-65, 1975-76, 1985-86, and 1994-95). The actual frequency range is from 0.002 to 0.5 day^{-1}, which corresponds to 2-500 days. Arrows are added to assist in determining the relative locations of peaks. The heliomagnetic polarity state (qA>0 or qA<0) for each period is also shown. Note that there does not appear to be any distinct frequency that consistently contains a peak in all four periods. There are no significant peaks observed in the high frequency region corresponding to period from 2 to 8-day. A flat spectrum for very short-term fluctuations (1.4×10^{-6} Hz $\leq f \leq 5.8 \times 10^{-6}$ Hz), have been observed. The well-defined peaks with harmonics (13.5- and 9-day) are clearly evident (in plots b, c, and d). At NAG (in plots b and c), no significant peaks corresponding to the solar rotation period or its harmonics are observed. The neutron monitors (DR, HUN, and WEL) PSD indicate that the cosmic ray series analyzed have nearly similar periodicities. The 1964-65 period PS shows that there is no a remarkable increase in the spectrum throughout the 8- to 100-day range. In plot 1a, although there are some hints of several spectral peak observed at DR and HUN, the greater one (and insignificant) corresponds to 25-day observed at HUN. Generally, no solar rotation influences have been observed. During the periods 1975-76, 1985-86 and 1994-95, the CRI power spectral at the solar rotation period (27 day) and its harmonics (13.5 and 9 days) are clearly evident. The amplitude of these peaks changes considerably between the three periods . The amplitude of the 27-day peaks changes inversely with the rigidity of the CR particles. There are some noticeable peaks at frequencies corresponding to periods from 45 to 66 days, which may indicate an unstable variation. Also, there is an evidence for a possible periodicity of 250-300 day in the all considered periods. Furthermore, there is no a break in the spectrum of used detectors for the four periods, even of high rigidities (MAW UG = 165 GV). Moreover, during the period (2 to 100-day), the maximum PS in each plot is at different frequency. In 1975-76 and 1994-95 periods, the maximum occurs at a period near 27d (DR and HUN in plot 1b and WEL and MAW UG in plot 1d), and at ~ 100d for NAG in plot 1b. At other time (1985-86) the period of high power is closer to 54d.

In Fig. 2 we plot the PSD of CRIs during the maximum solar activity years in the frequency range between 2.3 x 10^{-8} Hz and 5.8 x 10^{-6} Hz. Results indicated a flat spectrum for frequencies ≥ 1.4 x 10^{-6} Hz. However, for the 1968-69 and 1979-80 periods (plots 2a and 2b) four remarkable peaks at 9d, ~ 13.5d, 27.7d and 45d are present. Most of these peaks are wider than those in Fig. 1 and its have double-peak structures. This structure has already identified (Kudela et al, 1991). The process of CR modulations in and around solar maxima is complicated with probably many modulating factors involved. Figure 2
further indicates a broad peak near 250-300d (~ 0.7-0.8 year), which has been observed for the solar minima epochs. We found a very similar pattern of periodicity at the selected stations, giving evidence for a periodicity of 0.7-0.8 yr in the spectrum of CRIs. Mursula and Zieger (1999) attributed these periodicities to the changes in the coronal holes and to the active solar regions related to the coronal hole boundaries. Thus, our spectrum results of large-scale fluctuations in the CRIs have revealed the existence of a broad peak near 250-300 day, and narrower peaks at the solar rotation period and its harmonics.

In addition, the plots indicate a complicated structure of the spectra resulting from the superposed of the profiles with the different periodicities. The total profiles are determined by different periodicities rather than a superposition of different periodicities, which are stable in time. Shorter periodicities have different probability of occurrence in different epochs. The 1989-90 period (not shown) displayed only a broader profile with a remarkable one corresponds to 83d. No other significant peak has been obtained. It should be noted that extremely large Forbush decreases and an unprecedented number of ground level enhancements were observed in the 1989-91 period.

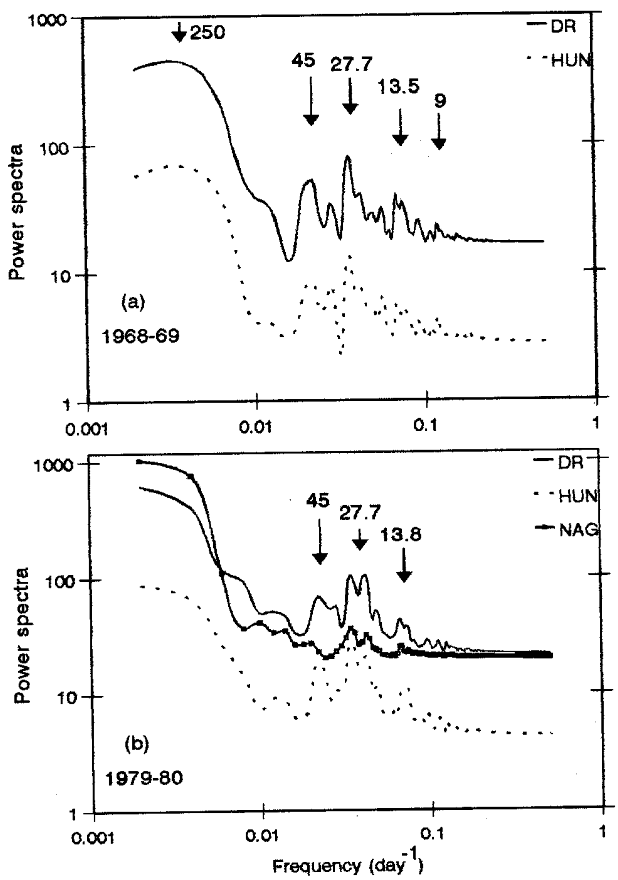

Fig. 2. The power spectra distributions derived from the daily mean of CRI recorded as a function of frequency for years of solar activity maxima (1968-69 and 1979-80).

From the two Figures 1 and 2, the CR power spectral density for regions with periodicities greater than 30-days shows a smooth variation without significant identifiable periodicity. In addition, there is a significant differences between the individual maxima spectral for different solar cycles. The single power law approximation is not appropriate for the whole frequency interval. The better approximation is a narrower interval of frequencies. The power spectral density P(f) of the time series is approximated to a power-law function: $P(f) \alpha f^n$, where n is the power law index and it is essentially used in describing the irregularity of the CR time variations.

We compare the spectral behavior at low frequency region 3.2x 10^{-3} d^{-1} ≤ f ≤ 3.2 x 10^{-2} d^{-1}, corresponding to periodicities 1-10 months for the minimum and maximum considered periods. It appears that the entire spectral shape (from 30 to 300d) may be considered as a broad increase with several peaks (45-, 66-, 83-, 100-, and 250-300d). In order to have a better look of the structure of the spectral density in the periodicity range > 30 days, we present Table 1, which gives the values of the exponent of power spectra for each considered detector, for the years of minimum and maximum solar activity, separately.

The comparison of cosmic ray modulation spectrum for the four successive solar minima indicates that, firstly the spectrum obtained in 1975-76 and 1994-95 solar minima appears to be softer than those in 1964-65 and 1985-86 (see DR, WEL, and HUN). Also, the power index is rigidity dependence. Secondly, for high rigidities (NAG and MAW UG), nearly each station has the same value of the power index n and independent on the solar polar magnetic field polarity state. For NAG SMT, the power index is 1.55 ± 0.16 for the 1975-76 (qA>0) and 1.6 ± 0.1 for the 1985-86 (qA<0). For MAW UG it is 1.4 ± 0.2 and 1.45 ± 0.1 for the two periods 1985-86 and 1994-95. So, for high rigidities, the rigidity dependence of cosmic ray modulations are practically lesser influences. The observed cosmic rays at high energies may suffer slight modulation in the heliomagnetosphere (Yasue and Mori, 1990). In conclusion, for low rigidities soft spectrum of CR modulations was obtained for the qA>0 epochs (1975-76 and 1994-95 solar minima) relatively to qA<0 epochs (1964-65 and 1985-86 solar minima) and it is consistence with the prediction of the drift-model. The fact is, the intensities of low-energy positively charged particles were higher in 1975-76 than in 1964-65 and 1985-86, (Reinecke and Potgieter, 1994).

Table 1. Values of power-law index, n, for the solar activity minima and maxima periods.

Station Name	Minimum Solar Activity Years				Maximum Solar Activity Years		
	1964-65 qA<0	1975-76 qA>0	1985-86 qA<0	1994-95 qA>0	1968-69 20th	1979-80 21st	1989-90 22nd
DR	1.39±0.2	0.59±0.18	1.05± 0.07	-	1.23±0.26	0.74±0.19	1.3±0.12
HUN	1.27±0.2	0.56±0.16	1.18±0.14	-	1.14±0.28	0.53± 0.23	1.21±0.17
WEL	-	0.73±0.17	1.1 ± 0.08	0.9±0.15	-	0.74± 0.19	1.29±0.14
NAG V	-	1.55±0.16	1.6 ± 0.1	-	-	1.24± 0.23	1.36±0.19
MAW UG	-	1.0 ±0.15	1.4 ± 0.2	1.45±0.1	-	0.74±0.18	1.4 ± 0.11

The 1968-69 and 1989-90 (SACs 20th and 22nd) solar maxima spectra are generally harder than those for 1979-80 (see Table 1). The PS of CR for even solar maximum years is higher than for the odd solar cycle. Thus, the CR power spectra of solar maxima for the SAC 20th and 22nd are much harder than for SAC 21st. At lower frequencies, our results indicated that the cosmic ray intensity power spectral exhibited a complex structure for different epochs. Also, there is no well relation between n and the sunspot numbers. Valdes-Galicia et al. (1999) reported that the PSD of sunspot numbers did not displayed the same periodicities found in CRIs. Kudela et al. (1991) showed that the power spectrum at periodicity corresponding to several months (3-6 months) appear to exhibit a dependence on 22-year periodicity caused by recurrence of reversal of solar magnetic fields. Even the periodicities larger than 27 days showed a similar behavior (Bishara and El-Borie,1990b; Kudela et al., 1991). Other (e.g., Smith, 1990; El-Borie, 1999) have revealed that the averages of CRIs every Carrington solar rotation (27-day) were inversely correlated with the tilts of the heliospheric current sheet during the qA>0 and qA<0 epochs. These observations indicated the significant of drift effects on the modulation of CRI at time scales of one month or more.

4. Conclusion

We investigate various CR rigidities over a wide range of frequencies 2.3 x 10^{-8} Hz to 5.8 x 10^{-6} Hz (periodicities from 2 to 500 days), over the period 1964-1995. Our analysis indicated several periods: a broad peak near 250-300 days (0.7-0.8 year), narrower peaks at 27d and its two first harmonics, and several peaks greater than one month. The two studied epochs showed different behaviors. The results of the power-law indexes have revealed the change in both shape and level of spectral power density with time and the rigidity of the particles. There are significant differences between the individual maxima spectral for different cycles and the correlation between the PSD with the polarity of the solar polar magnetic field is slightly well. The dependence of the power index n on the sunspot numbers is generally absent.

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References

Attolini, M.R., Cecchini, S., and Gali, M., *Proc. 15th Inter. Cosmic Ray Confer. (Plovidiv), 11,* 287, 1977.

Attolini, M.R., Cecchini, S., and Gali, M., *Nuovo Cimento, 7C*, 413, 1984.

Attolini, M.R., Cecchini, S., and Gali, M., *Proc. 21st Inter. Cosmic Ray Confer. (Adelaide), 6*, 47, 1990.

Bazilevskaya, G.A., Krainev, M.B., Stozhkov, Yu. I., Svirzhevskaya, A.K., and Svirzhevky, N.S., *Proc. 23rd Inter. Cosmic Ray Confer. (Calgary), 3*, 601, 1993.

Belov, A.V., Gushcina, R.T., and Soritina, I.V., *Proc. 23rd Inter. Cosmic Ray Confer. (Calgary), 3*, 605, 1993.

Bishara, A.A. and El-Borie, M.A., *Proc. 21st Inter. Cosmic Ray Confer. (Adelaide), 6*, 1, 1990a.

Bishara, A.A. and El-Borie, M.A., *Proc. 21st Inter. Cosmic Ray Confer. (Adelaide), 6*, 287, 1990b.

El-Borie, M.A., Duldig, M.L., and Humble, J.E., *Proc. 25th Inter. Cosmic Ray Confer. (Durban), 1*, 313, 1997a.

El-Borie, M.A., Duldig, M.L., and Humble, J.E., *Proc. 25th Inter. Cosmic Ray Confer. (Durban), 1*, 317, 1997b.

El-Borie, M.A., *Astropart. Phy., 10*, 165, 1999.

Fahlman, G.G. and Ulrych, T.J., *Mon. Not. R. Astro. Soc., 199*, 53, 1982

Jokipii, J.R. and Owens, A.J., *J. Geophy. Res., 81*, 2094, 1976.

Kudela, K., Ananth, A.G., and Venkatesan, V., *J. Geophy .Res., 96*, 15871, 1991.

Moraal, H., Potgieter, M.S., Stoker, P.H., and Van der Walt, A.J., *J. Geophy. Res.*, 94, 1459, 1989.

Mursula, K. and Zieger, B., *Proc. 26th Inter. Cosmic Ray Confer. (Utah), 7*, 123, 1999.

Owens, A.J. and Jokipii, J.R., *J. Geophy. Res.*, 77, 6639, 1972.

Owens, A.J. and Jokipii, J.R., *J. Geophy. Res.*, 79, 907, 1974.

Reinecke, J.P.L. and Potgieter, M.S., *J. Geophy. Res., 99*, 14761, 1994.

Smith, E.J., *J. Geophys. Res., 95*, 18731, 1990.

Valdes-Galicia, J.F., Caballero, R., and Hurtado, A., *Proc. 26th Inter. Cosmic Ray Confer. (Utah), 7*, 119. 1999.

Yasue, S. and Mori, S., *Proc. 21st Inter. Cosmic Ray Confer. (Adelaide), 6*, 276, 1990.