On the index of cosmic ray fluctuations at neutron monitor energies

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Abstract. Inhomogeneities of the interplanetary magnetic field (IMF), initiated from the Sun, influence cosmic ray (CR) fluctuations. An attempt to define the index of cosmic ray fluctuation variability based on 5–min data from two neutron monitors is made. It is suggested that the integral of the power spectrum density of cosmic ray fluctuations is used over time scales where the interplanetary magnetic field strongly influences cosmic rays at neutron monitor energies. This integral P1 ("the cosmic ray fluctuation variability index") can be employed as one of the parameters in predicting geomagnetic activity.

Key words: Sun – solar wind – cosmic rays – heliosphere

1. Introduction

Short-term variations of cosmic rays have been the subject of studies for many years (e.g. Dhanju and Sarabhai 1970, Owens and Jokipii 1973, Dorman and Libin 1980, 1984, and many others). One of the aims of cosmic ray fluctuation studies is to obtain information about the dynamics of magnetic field inhomogeneities in interplanetary space, on which the cosmic rays are scattered. Some authors use the cosmic ray fluctuation characteristic for the purposes of predicting geophysical phenomena (for a recent review see, e.g., Kozlov and Krymsky 1993).

The power spectrum density dependence on frequency domain and the appearance of selected periodicities in the spectra of cosmic ray time series has been the subject of many papers for a long time (starting with Dhanju and Sarabhai 1970, review of Dorman and Libin 1984 and references therein, Starodubtsev and Filippov 1984 and many others). The power spectrum density provides information about the distribution of harmonic components in different parts of the frequency domain of the signal. If the signal is affected by processes with characteristic time T (or frequencies f = 1/T), the changes in the driving process (however, not only these) can cause changes in the power spectrum density in the appropriate frequency domain. In our earlier study (Kudela et al. 1992) we used the power law index of the spectrum, ν, to characterize its shape. However, the power spectrum is often of a very complicated form, and the power–law

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frequency approximation over the whole frequency range is a very rough characteristic. On the other hand, the spectrum varies from day to day.

Our task is to deduce a simple index, describing the cosmic ray fluctuation characteristics, which reflects the variability of the primary cosmic ray intensity. We have examined two years (1991–1992) of 5–min records from two neutron monitors with different cut–off rigidities, namely Calgary and Lomnický Štít, for their power spectrum characteristics on a daily basis.

The variability of the shape of the spectra is correlated with several geomagnetic indices, and it is shown that the power spectrum density in the low–frequency domain, where interplanetary magnetic field inhomogeneities can affect the cosmic ray intensity for day 'i', displays a higher correlation with the average geomagnetic activity index Dst for the next day 'i+1' than for given day 'i'. A similar type of asymmetry is observed for Ap and Kp geomagnetic indices.

2. Method and data

5–min pressure corrected data from two neutron monitors were used for the period January 1, 1991 – December 31, 1992:

1. **Calgary** (latitude 51° 05' N, longitude 114° 08' W, vertical cutoff 1.09 GV, count rate approximately 2×10^4 per 5–min) and
2. **Lomnický Štít** (latitude 49° 11' 20" N, longitude 20° 14' 42" E, vertical cutoff 3.84 GV, count rate approximately 1.3×10^5 per 5–min).

Only data covering the whole day, i.e. 288 measured points, were included in the analysis. Of the 731 days for the years 1991–1992, 724 sets of values from Calgary and 691 sets from Lomnický Štít were constructed.

This represents a total of 685 days covered by data from both stations simultaneously. The analysis is based on daily characteristic values of the power spectrum of the CR signals and compared with ΣKp, Ap and Cp indices taken from the bulletin *Solar Geophysical Data.* To provide comparison with the characteristic geomagnetic field depression for any one day, the ΣDst value was also included.

To estimate the power spectrum we used the indirect method based on the Fourier transform of the autocorrelation function according to (Box and Jenkins 1974). Given N data points (there are N = 288 'the 5–min' values in one day) autocorrelation $r_k = c_k/c_0$ for k = 0, 1, 2, ..., N-1 is estimated as

$$c_k = (N)^{-1} \times \sum_{t=1}^{t=N-k} (x_t - x) \times (x_{t+k} - x) \qquad (1)$$

where the summation is taken over t = 1, 2, ..., N-k and 'x' is the average of 'x_t'. The periodogram is defined as $I'(f_i) = (N/2) \times (a_i^2 + b_i^2)$ and involves $q = (N-1)/2$ values ($i = 1, 2, ..., q$), where $f_i = i/N$. The definition of the periodogram is modified in (Jenkins and Watts 1968) and it is called the sample spectrum:

$$I(f) = (2/N) \times (a_f^2 + b_f^2) \tag{2}$$

for frequencies $0 \leq f \leq 1/2$. Compared to the periodogram, the sample spectra can be used to estimate the amplitudes of the sinusoidal component at any particular frequency f, not only at $f_i = i/N$. This is useful in estimating the integral of the power spectrum density in a given interval of frequencies. According to (Box and Jenkins 1974), the sample spectrum, I (f), is related to the estimates of the autocorrelation function c_k as

$$I(f) = 2 \times (c_o + 2 \times \sum_{k=1}^{k=N-1} c_k \times \cos(2\pi f k)) \tag{3}$$

where the summation is over k = 1, 2, ..., N-1 and $0 \leq f \leq 1/2$.
For $N \longrightarrow \infty$, the power spectrum density is obtained as $p(f) = \lim_{N\to\infty} E[I(f)]$, where E stands for 'Expectation'.
The dispersion of the process is $\sigma^2 = \int_0^{1/2} p(f)df$.
Power spectrum density 'p (f)' shows how the dispersion of the time series, composed of a mixture of harmonic functions, is distributed in the continuous interval of frequencies.

To characterize this distribution in the neutron monitor time series, we divided, as a first approach, the real frequency interval into two frequency domains (for the 5–min data):
domain 1 – with frequencies (f') below 2.8×10^{-3} Hz , and
domain 2 – with frequencies above this value.
We have taken T '= 1 hour (and correspondingly $f'_c = 1/T'$) as a rough estimate of the upper frequency boundary for the time variations which can be affected by the interplanetary magnetic field under typical quiet conditions (Bazilevskaya and Struminsky 1993). On the basic scale of $f \in (0, 0.5)$ we have the limits : $f_0 = 0.0034$ Hz, $f_c = 0.0833$ Hz and $f_u = 0.5$ Hz. For each day and at both stations, we have computed the values

$$P1 = \int_{f_0}^{f_c} p(f)df \tag{4}$$

$$P2 = \int_{f_c}^{f_u} p(f)df \tag{5}$$

and fitting the form

$$p(f) = k \times f^{-\nu} \tag{6}$$

separately in the two respective frequency intervals, for the values ν_1 and ν_2.

Table 1. The results of correlation analysis of the cosmic ray fluctuation characteristics (i.e. P1, ν_1, P2, ν_2 when T = 1 hour and where '1' and '2' stands for low– and high–frequency domain) for the Calgary and Lomnický Štít monitors.

	P1	ν_1	P2	ν_2
r	0.89	0.38	0.14	0.05

3. Results

3.1. Comparison of Calgary and Lomnický Štít "cosmic ray fluctuation variability indices" (approximated by P1, P2, ν_1 and ν_2)

For each day in the interval 001/1991 - 366/1992 we have constructed the spectra and deduced values P1, P2, ν_1, ν_2, for both cosmic ray stations, Calgary and Lomnický Štít. In many instances similar increases in P1 at both stations, indicating a strong contribution of low frequency components in the cosmic ray signal, are seen in the data (Kudela et al. 1994), some of them in conjunction with strong decreases in the cosmic ray time profile. We have checked the correlations of the respective characteristics at the two stations.

Table 1 summarizes the correlations based on two years of daily values P1, P2, ν_1, ν_2, at the two respective stations (Calgary and Lomnický Štít). As shown in Table 1, the highest value of the correlation coefficient is found for P1, and is equal to 0.89, which is a statistically significant value for 685 points. Therefore, cosmic ray fluctuation characteristic P1 is very well correlated at the two above–mentioned cosmic ray stations. The power–law indices, ν_1, display lower correlation ($r = 0.38$).

On the contrary, the higher frequency region has uncorrelated characteristics at the two above–mentioned cosmic ray stations (for P2 we found $r = 0.14$ and for ν_2 $r = 0.05$).

3.2. Cross-correlation coefficients of Calgary cosmic ray fluctuation variability parameters

For the Calgary neutron monitor, the correlation values of cosmic ray fluctuation variability parameters are shown in Table 2, in the two appropriate frequency domains.

Anticorrelation between Calgary cosmic ray intensity (CNI) and value P1 is expected, since the strongest changes in the fluctuation characteristics appear around the sharp cosmic ray decreases. However, this P1–CNI correlation is − 0.19; (which according to Bolshev and Smirnov 1983, p. 250 represents the interval between 0.15 to 0.24 for a confidence level of 0.95). Thus value P1 can be assumed as a characteristic, relatively independent of the cosmic ray intensity itself and correlated at two neutron monitors with different cutoffs and acceptance cones.

Table 2. The correlation matrix estimated for P1, ν_1, P2, ν_2 and cosmic ray intensity (CR) variables (when T = 1 hour), as measured at Calgary.

	P1	ν_1	P2	ν_2	CNI
P1		−0.33	0.19	−0.27	−0.19
ν_1			0.06	0.12	0.30
P2				−0.21	0.11
ν_2					0.10

It should be noted, that the cross–correlations between characteristics P1, P2, ν_1, ν_2, and between any of these characteristics and the Calgary cosmic ray intensity itself (CNI), are low.

3.3. Comparison of "the average cosmic ray fluctuation variability index (P1')" and geomagnetic indices

Table 3. The values of cross-correlation coefficients of parameter P1' (where $P1' = 1/2(P1_C + P1_L)$, i.e. average of two normalized P1 indices for Calgary and Lomnický Štít) versus geomagnetic indices for time lags between −2 and +2 days.

time lag	−2	−1	0	+1	+2
sum Kp	0.095	0.113	0.248	0.260	0.154
Ap	0.066	0.092	0.341	0.376	0.155
Cp	0.095	0.108	0.228	0.211	0.138
Dst	−0.059	−0.080	−0.177	−0.379	−0.231
Dst for CR	−0.385	−0.409	−0.395	−0.338	0.307

Once the time series of the above–mentioned characteristics of cosmic ray fluctuations and of a few geomagnetic indices have been constructed, it is interesting to review the cross–correlations of these time series. The results are displayed in Table 3.

As the leading parameter (the first time sequence) the values of P1' are adopted, where $P1' = 1/2(P1_C + P1_L)$ as well as L and C stands for Calgary and Lomnický Štít). This is the "first" time sequence P1' (i.e. with day index'i') whereas the "second time sequences" (with day index i + time lag in days) are the time series of geomagnetic activity indices.

The assymetry with respect to '0 timelag' of the cross-correlation functions is viewed in the same sense, i. e. for time lag +1 day. The geomagnetic sequences are delayed 1 day relative to the average cosmic ray fluctuation variability P1' sequence. The cross-corelation values does not decay as for a lag of −1 day. This feature is seen for Kp, Ap and average Dst indices.

The different behaviour of these dependences for Lomnický Štít and Calgary was reported in (Kudela et al. 1994), if the "leading" time series was the cosmic ray intensity itself (CR). There is then no indication of a similar effect. For Kp, Ap and Cp the cross-correlation at time lag −1 day is higher than at +1 day, and with the exception of average Dst, the value at −1 day is higher than that at time lag 0 day (see the last line of Table 3).

4. Discussion and summary

Dividing the power spectrum density into two parts, low frequency (1) and high frequency (2), clarifies the behaviour of the variability of cosmic ray time variations based on 5–minute data and analyzed on a daily basis. We can summarize the analysis as follows:

The cosmic ray fluctuation variability index (here approximated by P1): The integral of the power spectrum density over the low frequencies where, in principle, the interplanetary magnetic field can have an effect on the cosmic ray time variations, estimated as P1, is the value which has a similar time profile at the two stations in the analysis. We suggest this is a signature of the effect of phenomena in the interplanetary magnetic field distribution on cosmic rays. The two–year series of data is sufficient to draw this conclusion. This characteristic is reproduced better at two widely separated stations, such as Calgary and Lomnický Štít, than the power–law index of the spectrum (ν), used in our earlier study (Kudela et al. 1992). This also applies within the low–frequency domain, i. e. for ν_1.

We suggest that P1 can be used as a basis for defining the variability characteristic of cosmic ray time fluctuations. This characteristic is not strongly related to the average cosmic ray intensity, and thus can be assumed to be an independent characteristic of the cosmic ray intensity profile.

For a better definition of the proper index of cosmic ray fluctuation variability, more stations with different cutoffs could be used to check the validity of the above–mentioned conclusion, and the analysis could be applied to a longer time period. For high–latitude stations the signal of cosmic ray intensity is affected by the presence of short–term increases such as ground level events which, of course, also lead to increases in P1. These events may prove deceptive if conclusions deduced from P1 only from high–latitude stations are used.

The high–frequency part of the spectrum, characterized both by the power–law spectral index (ν_2) and by the integral over spectral density (P2), at periodicities smaller than 1 hour, has a different character at the two stations; it displays no clear "global" behaviour, which we ascribe to the effects of processes probably of a "local" origin.

Average CR index P1' versus geomagnetic activity indices (time–lags): One of the results is the fact that the maximum of the cross–correlation of P1 versus Ap, Kp, and versus average Dst, using the daily data, does not occur exactly at the zero–day lag, but probably with a time lag of between 0 and

1 days. The effect more distinct for Lomnický Štít, with a higher cut–off, than for Calgary, where effects of solar cosmic rays may influence the picture. This result, if confirmed also on other data sets and in other epochs, could be important for understanding the relevance of cosmic ray time series for predictions of nonstationary processes in the magnetosphere. The redistribution of the interplanetary magnetic field inhomogenities can be reflected in the low–frequency part of the power spectrum density of cosmic rays. The use of solar wind parameters (density and bulk speed) and of the magnetic field near the Earth for predicting geomagnetic activity is limited due to their "local" character. These observations are used successfully in predicting Dst (Lundstedt and Wintoft 1994). The authors show that the use of neuron network approach is useful for this type of prediction. From the preceeding 8 hours of plasma and magnetic field data, the Dst value for the next hour can be reproduced well on the test data. Since the cosmic ray time variations are not affected only by the "local" parameters, (i.e. magnetic field near the Earth), but reproduce the distribution of magnetic inhomogenities throughout the whole heliosphere, cosmic ray may be important in extending the analysis of (Lundstedt and Wintoft 1994) in trying to predict the geomagnetic parameters from plasma and magnetic field data to times longer than one hour. For such types of studies the inclusion of cosmic ray variability data, such P1 discussed here, may prove relevant. To include the cosmic ray variability index into the scheme of Space Monitoring suggested by (Dorman and Libin 1993) could also be interesting. Since there is an indication that the cross–correlation maxima between P1 and geomagnetic indices are biased to positive time lags (here the quantization is restricted to 1 day), cosmic ray variability can be characterized by P1 more smoothly by shifting the window by a few hours, and the relevance of using P1 for the predictions could be examined in detail. Since we have seen that the "low–frequency behaviour" of cosmic rays gives a consistent picture of the variability of primary cosmic rays, it would also be interesting to check the data based on a lower time resolution, e.g. half–hourly. Thus, from the practical point of view, this could be simpler, with respect to the method of monitoring nonstationary processes.

However, caution must be taken in drawing "predictional" conclusions from this type of study. Although the data demonstrate that cross–corelations are biased towards positive time lags, the values of the cross–corelations themselves are relatively small. Thus it is premature to declare the usefulness of the P1 parameter alone for the predictions of geomagnetic activity and other nonstationary processes within the magnetosphere. We feel that the first step in the continuation of this work, after checking larger amounts of data from more stations and longer periods, will be the inclusion of "the cosmic ray fluctuation variability index" (here approximated by P1) into the scheme of neuron network prediction (used e.g. by Lundsted and Wintoft 1994). If the prediction with P1 included proves to be better than that based only on solar wind and plasma parameters, the usefulness of P1 will be confirmed.

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