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Nonlinear Processes in Geophysics

On the character of cosmic ray variations at $f > 2 \times 10^{-5}$ Hz

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Abstract. We examine the time series of cosmic ray (CR) intensity recorded by two neutron monitors (NMs) at medium latitudes for scaling properties on time scales shorter than the diurnal variation. Scaling of the data with 10 sec as well as 1 min resolution is shown to be complicated, indicating that there is probably not a unique process governing the CR fluctuations in the whole interval studied. For T < 20 min the general characteristics are similar to those of white noise. Above 40-60 min the scaling characteristics are dependent on the level of interplanetary disturbance. This is consistent with the concept of scattering CRs by inhomogeneities of the interplanetary magnetic field (IMF). With increasing interplanetary turbulence the dimensionality of the CR time series decreases. The region of stable scaling is, however, narrow, only up to 6 hours. Multifractality signatures in the region 1-6 hours are similar to those in the IMF, however the deviations from monofractality are relatively small.

1 Introduction

The fractal and/or multifractal structure of the IMF and of the temperature and the density of the solar wind has been examined in several studies (e.g. Burlaga and Klein, 1986; Burlaga, 1991 a,b,c; Burlaga, 1992). As a contrast, the character of CR times series observed at NM energies, i.e. those influenced by the IMF, has been studied in only a few papers (Yasue and Mori, 1990). At higher energies, the monofractal character of CR intensity is reported by (Aglietta et al., 1993). This monofractality may be due to the fact that high energy CRs are insensitive to the redistribution of the small-scale irregularities in the heliosphere which in turn arises due to the changes in solar and interplanetary activity. The use of the fractal dimension for characterization of the time series from meson telescopes was shown in Yasue et al. (1993). Several years of hourly measurements of CR at two NMs, namely Calgary and Lomnický štit (LS), show scaling with the fractal structure for the periods 32-256 hours (Kudela and Venkatesan, 1993).

In recent years, the search for solar neutron responses in the NM data led to the increase of time resolution of NM measurements (e.g. Valtonen et al., 1987; Takahashi et al., 1990; Ye Zhonghai and Feng Hua, 1990). There are reports on several changes in fluctuation characteristics of NM time series with short-time resolution during non-stationary processes in interplanetary space like Forbush decreases and solar flare particle events (e.g. Nagashima et al., 1990; Flückiger, 1990). Despite the fact that on several NMs the measurements are run with a time resolution of 1 min or better, and much observation material is ready for analysis, there is a lack of description of general characteristics of these time series. We are using 1 min data from two NMs, Jungfraujoch (JJ) and LS, to deduce the common characteristics of such time series, to check the adequacy of a description of the data according to the concept of fractality, and to investigate the scaling of higher moments of the statistical distribution of the data.

2 The data

We are using 1 min pressure corrected data for the period March 1991 from two NMs: JJ (latitude 46.55° N, longitude 7.98° E, vertical cutoff 4.48 GV, altitude 3570 m, count rate approx. 2×10^4 per 1 min) and LS (latitude 49.20° N, longitude 20.22° E, vertical cutoff 3.84 GV; altitude 2634 m, count rate approx. 2.6×10^4 per 1 min). An additional set of data is 10 sec measurements from LS during November 1-10, 1992. These data are from the joint experiment U. of Turku, Finland and IEP SAS Košice, Slovakia. The short gaps in the data are filled by linear interpolation.

To check the consistency of the methods used in the following analysis, we have generated test data as time series by adjusting power spectrum distribution and random

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phases. Since the fractal analysis is related to the power spectrum analysis, one natural way of testing the procedures used in fractality checking is to generate the time series with the adjusted power spectrum density. If the power spectrum of the time series I_t is given {i.e. the form of P(f), in discrete f_i, $P(f_i) = (n/2)(a_i^2 + b_i^2)$ where $a_i = (2/n) \Sigma I_t \cos(2\pi f_i t)$, $b_i = (2/n) \Sigma I_t \sin(2\pi f_i t)$, summation is over t = 1,...,n, $f_i = i/n$, n is an odd number (Box and Jenkins, 1976)}, the corresponding time series is not determined uniquely, since the phases are not fixed. Any set of random phases adjusted in such a way that real values of time series are produced can provide a realization of the temporal process. We have used the algorithm similar to that of Owens (1978), and generated 2^{14}-point time series with $P(f) = \text{const.}\times f^{-\alpha}$ where α = 0, 1, 5/3, 1.75, 2 and 3, respectively with phases uniformly distributed over (0, 2π). For the power spectrum analysis we used the FFT method.

3 Power spectrum properties

A common, widely used method which we also apply to the data is the power spectrum analysis. For the estimation of the power spectrum we are using the indirect method based on Fourier transform of autocorrelation function according to Box and Jenkins (1970). Having N data points (the 5 min values for one day) the estimation of autocorrelation $\rho_k = c_k / c_o$ for k=0,1,2,...,N-1 is constructed with

$$c_k = (N)^{-1} \Sigma (x_t - x)(x_{t+k} - x) \quad (1)$$

where the summation is taken over t=1,2,...,N-k. The value x is the average of x_t. The periodogram as defined in Box and Jenkins (1970) and Jenkins and Watts (1968) is called the sample spectrum and is the cosine transform of the autocorrelation function

$$I(f) = (2/N)(a_f^2 + b_f^2) \quad (2)$$

for frequencies 0 ≤ f ≤ 1/2. As an additional feature compared to the periodogram defined in Box and Jenkins (1976), 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 power spectrum density in a given interval of frequencies. According to Box and Jenkins (1970), the sample spectrum, I(f) is related to the estimates of autocorrelation function c_k

$$I(f) = 2\,[c_o + 2\Sigma c_k \cos(2\pi f k)] \quad (3)$$

where the summation is taken over k = 1,..., N-1 and 0 ≤ f ≤ 1/2.

The power spectra of the two sets of data, JJ and LS, for the period March 1-16, 1991, were examined by the above mentioned method (23040 points with only 15 data gaps).

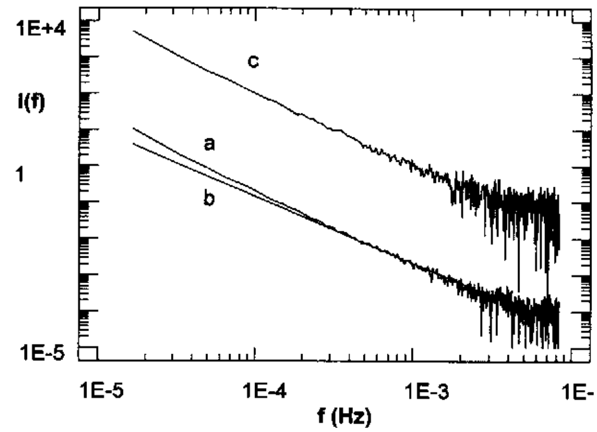

Fig. 1. Power spectra of 1 min NM data from LS (curve a) and JJ (curve c, multiplied by 1000) for the period March 1-16, 1991. The power spectra are computed according to (3). Curve b is a fit to the LS power spectrum using a single power law index.

This interval is characterized by low level interplanetary activity. The spectra I(f) are displayed in Fig.1. The form of I(f) is similar on both stations over a wide interval of periodicities. The form is not strongly different from $f^{-5/3}$ which is expected for the Kolmogorov spectrum describing inertial turbulence in an incompressible fluid. However, unlike the IMF power spectrum, the CR power spectrum is not ideally fitted by a single power law index having clear physical meaning. Using the approximation $I(f) = k\times f^{-\alpha}$, we obtained α = 1.81 ± 0.04 for LS and α = 1.72 ± 0.06 for JJ. The transition from the fitted "global" index towards steeper spectra (close to 2.0) is seen at lower frequencies ($f < 2\times 10^{-4}$ Hz), which could correspond to ordinary Brownian motion, rather than to the Kolmogorov index 5/3. With the increasing f the power law approximation gives lower correlation and larger errors, and the index α is not determined with a sufficiently low error to distinguish conclusively between 2 and 5/3.

4 Scaling below the diurnal periodicity

To determine the scaling properties of the signal of short time resolution data from NMs, we are using two methods, (a) the determination of the scaling exponent and (b) the method used by Burlaga and Klein (1986).

The dimension of the temporal process described by self-similarity properties of the signal can be obtained assuming that the distributions of values [I (t+τ) - I (t)] has the same properties as the distribution of n^{-H} [I (t+nτ) - I (t)] where H is a constant (Aglietta et al., 1993; Bergamasco et al., 1993). We start by assuming a simple, monofractal scaling, although it is a special restrictive case of scale invariance and probably does not describe the real situation (Lovejoy, 1995). The reason is that at higher energies the behaviour of CR time series could be described in this approach (Aglietta et al., 1993; Bergamasco et al., 1993), and we wish to compare the lower energy CR behaviour with those results. The value H is obtained as the slope of linear interval of $\Delta I(n\tau)$ vs $n\tau$ in a log-log plot. The consistency of the conclusions about the fractal properties requires the equality of the dimensionalities obtained from the above mentioned methods.

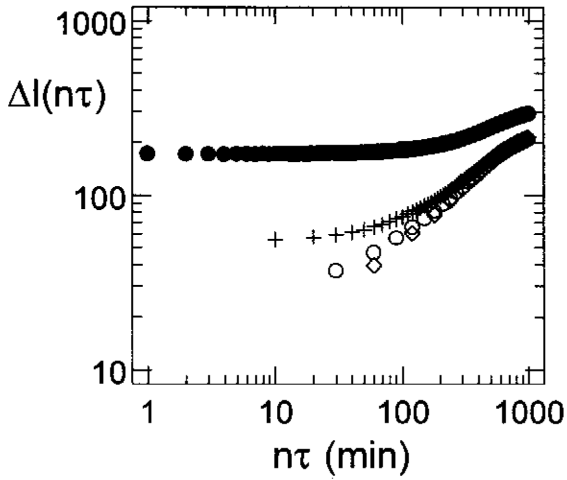

Fig. 2. Scaling of 1 min NM data from JJ. 2^{14} data points from 00 UT on March 1, 1991 are taken. The variance, ΔI ($n\tau$) vs $n\tau$ is displayed. The effect of data averaging is seen. The three sets of data correspond to: τ = 1 min, original data (full circles); τ = 10 min (crosses), τ = 30 min (open circles), and τ = 60 min averages (rhomboids).

Figure 2 displays the scaling properties of the 1 min signal taken as 2^{14} points from JJ March, 1991 data in the plot $\Delta I(n\tau)$ vs $n\tau$. For the original data (full circles) τ = 1 min; the points on other curves correspond to 10 min data (crosses), 30 min (open circles) and 60 min averages (rhomboids). A similar character was found in the 10 sec data. There are two apparent characteristics: (i) the effect of noise leads to the underestimation of the scaling exponent, which is similar to the finding in Bergamasco et al. (1993), and (ii) only a small stable linear interval is seen from approximately 1 to 6 hours.

The fractal dimension can be alternatively estimated by the method used in Burlaga and Klein (1986); Mandelbrot (1982); or Higuchi (1988). This method was used also for high energy CRs (Bergamasco et al., 1993). The length of the curve, Λ, is measured $\Lambda(n\tau) = \Sigma_i \text{ abs}\{I(t_i + n\tau)-I(t_i)\}$, i=n,2n,3n,...,. Λ means the length of the "histogram" of the curve for different averaging of time series defined by $n\tau$. For a fractal self-affine signal, $\Lambda(n\tau)$ behaves as $n^{L-1}$and as n^{-S}, where L will be defined in equation (6). In the method of Burlaga and Klein (1986) the length of the curve is measured at equidistant points of the scale log n (n is 2^m, m is integer) and the slope of linear interval of log Λ vs log n of these two values, -S, is obtained. The length can be measured for any n. This approach is used in Higuchi, (1988), Yasue et al. (1993), and Bergamasco et al. (1993).

The procedure is the following. We take 2^{14} data points {I(1),I(2),..., I(16384)}. In the first step (m =0) we take the original data and the "length" $\Lambda(2^0) = |I(2) - I(1)| +$ $+ | I(3) - I(2) | + ... + |I(16384) - I(16383)|$. In the second step (m=1) we are averaging the data over 2, and construct $\Lambda(2^1) = | \{I(3) + I(4)\}/2 - \{I(1) + I(2)\}/2| + ...$ $+ | \{I(16383)+I(16384)\}/2 - \{I(16381) +I(16382)\}/2|$. Then follow steps m=3,....,n-1. Thus for each m the procedure gives the length of the curve, $\Lambda(2^m)$ constructed from averages of the original data over 2^m points; m = 0,1,..,n-1. The linear intervals in the plot $\log(\Lambda)$ vs $\log(2^m)$ provide the information on the scaling.

The test series generated as f^0, as well as other series with adjusted form of power spectrum density, were evaluated by the above mentioned procedure. Defining the q-th order structure function as $<|\Delta I(\Delta t)|^q> \approx \Delta t^{K(q)}$, the value L = K(1). For the simple scaling K(q)=Hq is linear in q, and α = K(2) + 1. For this simplest case, similar to Bergamasco et al. (1983) , when L is deduced from the plot, the validity of the relation $\alpha = 2L + 1$ was confirmed on the test data, even if L < 0. For the white noise case, formally L = -0.5 and S = 1.5.

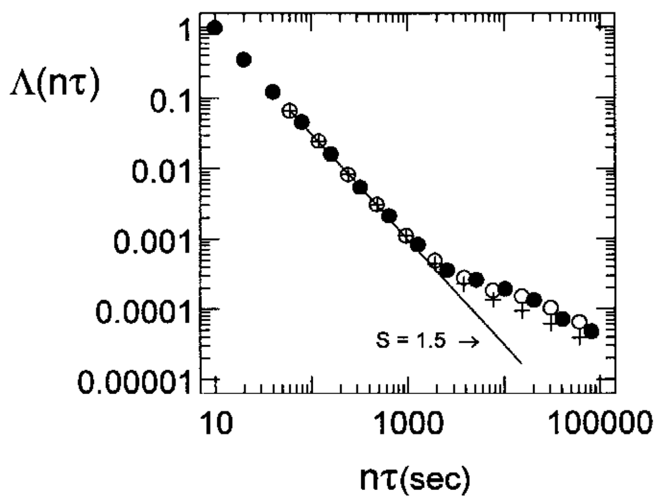

Fig. 3. The yardstick length exponent for 10 sec LS data from November 1-10, 1992 (full circles), and from 1 min JJ data in two periods in March, 1991 (crosses: quiet period, open circles: disturbed period including the large geomagnetic storm on March 23-24, 1991). The length Λ at different averagings is displayed, the averaging time is in sec. Note that the slope 1.5 is well seen for all data up to approximately 20 min.

The result of the method described above is seen in Fig. 3. Two sets of 1 min data (differing in the level of interplanetary disturbance) and 10 sec data are plotted in the same graph. The normalization is adjusted so that Λ (τ =10 sec) = 1. For all data sets the behaviour is clear with

S = 1.5 up to at least 20 min. For longer times, a deviation from that dependence is seen, the amplitude of which is a function of the interplanetary activity.

5 Scaling of the higher moments

We have examined the scaling of higher moments of distribution of the NM time series using the method similar to that described in Burlaga (1991c). We have $N = 2^{14}$ data points. We construct the averages, $I_n(t)$, over subsequent 2^n points and ascribe them to t in the center of that interval, (n = 0,1,2,...,13). Values having the meaning of probabilities of occurrence of the values $I_n(t)$,

$$p_n(t) = I_n(t)(2^n/N) \quad (4)$$

are also constructed (note $\Sigma\, p_n(t) = 1$, summation over t = 1,..., $N/2^n$). The data are normalized so that $< I_o(t) > = 1$. For each averaging, 2^n, the q-th moment of statistical distribution, $M_n(q) = E\,[\{p_n(t)\}^q]$ is defined, which in discrete form means

$$M_n(q) = \Sigma n(p_n(t))[p_n(t)]^q \quad (5)$$

where summation is again over t = 1,..., $N/2^n$. Similar to the multifractal structure of the aggregate (Coniglio, 1986), where the mass, M, scales with the linear size, L, as

$$M(q) = \Sigma n(p)p^q \sim L^{-(q-1)D_q} \quad (6)$$

Similar to the notation of Coniglio (1986) instead of L (the aggregate size) we have N, and instead of ℓ (the linear size of cells) we have 2^n. Thus the q-th moment has the scaling symmetry

$$M_n(q) \sim (N/2^n)^{-(q-1)D_q} \sim (2^n/N)^{\gamma(q)} \quad (7)$$

Since $M_n(q) = (N/2^n) < p_n^q >$, we relate $< p_n^q > \sim (2^n/N)^{\gamma(q)+1}$, or

$$< I_n^q > \sim < p_n^q > (2^n/N)^q \sim (2^n/N)^{\gamma(q)-q+1} = (2^n/N)^{s(q)} \quad (8)$$

By plotting $\log < I_n^q >$ versus $\log(2^n)$, the values s(q) are deduced from the linear intervals. A multifractal object is characterized by a continuous spectrum of indices $f(\alpha)$. Values α and f can be obtained from the knowledge of D_q, i.e. from

$$\alpha(q) = d/dq\,[(q-1)\,D_q(q)]$$
$$f = q\,\alpha(q) - \tau(q) = q\,\alpha(q) - (q-1)\,D_q(q) \quad (9)$$

according to Halsey et al., (1986). Multifractal indices can also be studied by another method, called double trace moment technique as used in the studies Tessier et al. (1993) and Schmitt et al. (1993). Different methods of studying multifractality are referenced in Davis et al. (1994).

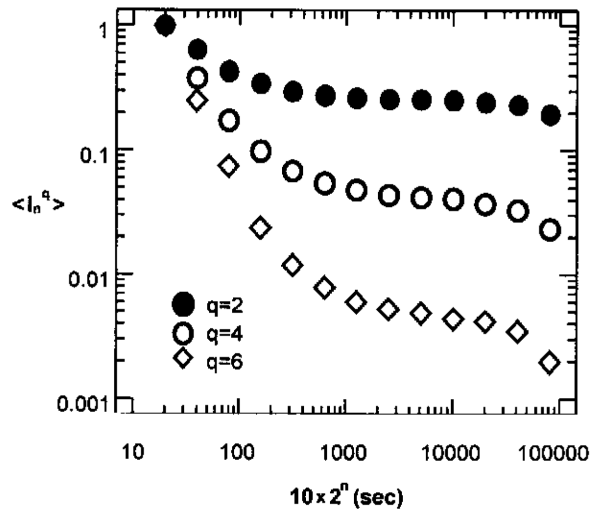

Fig. 4. Plot showing the properties of scaling higher moments of the CR short time data records. The values $< I_n^q >$, the q-th statistical moments (around the mean) of the averages over 2^n data points, versus (2^n) are displayed in the log-log scale. For definitions, see part 5. Data from 10 sec measurements at LS are used, n = 1, ..., 13 points are shown.

We have examined the values $< I_n^q >$ and plotted them in log-log plot versus 2^n. One data set from 10 sec measurements and another from 1 min data in March 1991 were analyzed to deduce the values s(q). Figure 4 shows the selected moments of the distribution for the 10 sec data. There is a relatively narrow interval of times for which the linear behaviour between $\log < I_n^q >$ and $\log(2^n)$ for all q studied can be taken, namely between 2560 sec and 20480 sec. For the 1 min data a similar interval was found. Figure 5 displays two selected moments of the 1 min data and a comparison with the expected scaling for normally distributed data. If s(q) is constructed from the interval 2560-20480 sec, the values have a dependence on q as shown in Fig. 6. There is a deviation seen from linearity which is expected for the multifractal character of the data. However the deviation is not very clear assuming the present statistical accuracy. According to Lovejoy (1994) to test for multifractality, one must concentrate on the low order moments ($0<q<2$). Testing the available CR data for different periods, however, we did not find a conclusive stable value of q_s for which the linearity of s(q) is valid in the region $q > q_s$. It should be mentioned that recent results on geomagnetic time series from ground based magnetograms (Vörös et al., 1995) have not shown clear evidence of multifractality either. Cosmic ray variations probably have an unclear degree of fractality, especially at time periods of less than 1 hour, where the influence of the IMF is negligible and where, subsequently, the geomagnetic field variations may be the dominant cause of CR variations.

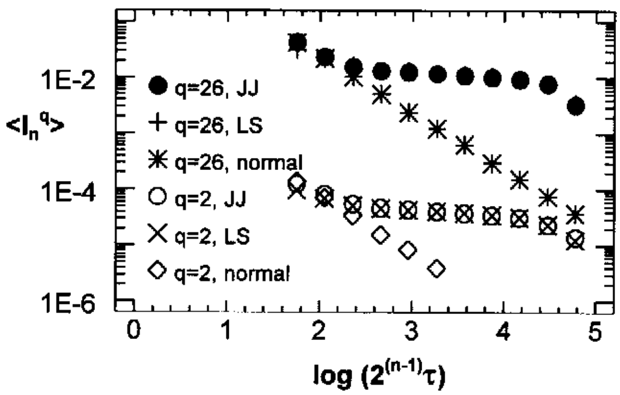

Fig. 5. Example showing (i) the similar scaling characteristics for the time series of CR data measured at two different NMs during the same time interval (March 1-16, 1991) and (ii) the difference of the scaling of CR time series and of normal distribution data with the same variance, $n = 1, ..., 11$, $\tau = 60$ sec.

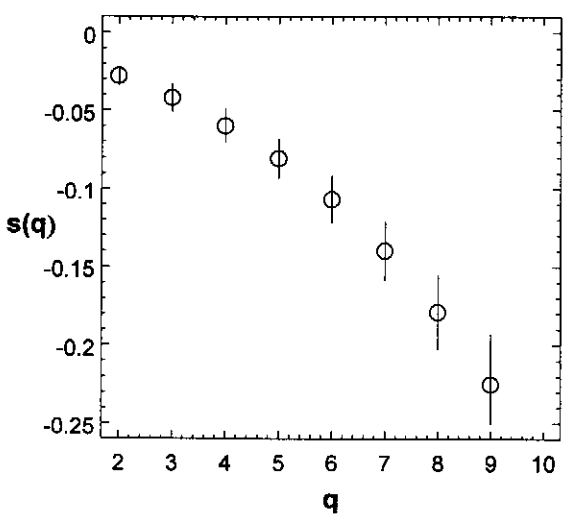

Fig. 6. Values of the slopes, s(q) for selected moments and interval 2560-20480 sec, obtained from Fig. 4 are displayed. The nonlinear behaviour of s(q) is seen; however, the deviation from linearity is not strong.

6 Discussion

Cosmic ray short term variations 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 these studies at NM energies is to deduce the information about the dynamics of magnetic field inhomogeneities in interplanetary space responsible for CR scattering. Some works use the CR fluctuation characteristics for the purpose of predicting geophysical phenomena (for a recent review, see e.g. Kozlov and Krymsky, 1993). An alternative description of the most common analysis of the power spectra is the fractal description applied here to the short time resolution CR data. This description could be a useful additional approach to the systemization of the fluctuation characteristics, as by S or H.

The time series from high energy primary CRs are only marginally affected by solar effects and have stochastic monofractal character (Aglietta et al., 1993). At lower energies and at NMs with relatively high count rate, the effect of multifractality due to its character at the IMF inhomogeneities would not be an unexpected feature. Such structure, if clearly seen on large amounts of data and in larger numbers of NM time series, is not in contradiction with monofractal structure seen at higher energies.

The analysis performed here has shown that the simple scaling of CR time series (characterized by a single scaling exponent) is not appropriate for the wide interval of characteristic times from tens of seconds up to one day, contrary to longer time scales. There are probably several processes which simultaneously determine the scaling of CR time series. The most important of them is the scattering of CRs on inhomogeneities of the IMF. An effective scattering of CR particles in the IMF can be expected only when the magnetic irregularities have a characteristic dimension which is larger than the gyroradius of the particle. This makes constraints on the minimum characteristic time of CR variations due to interaction with the IMF irregularities (Bazilevskaya and Struminsky, 1993). For 10 GeV particles, solar wind speed v = 400 km/sec, and B = 5nT, the variations due to the IMF can be observed at $T > T_{min} = 40$ min. Figure 2 in Kudela and Venkatesan (1995) shows that different periods, characterized by different levels of interplanetary activity and the associated turbulence, yield different scaling of the CR time series above the interval 20-40 min. Below 20 min the effect on scaling of CRs is negligible. This supports the idea that the fluctuation spectra and scaling properties are significantly influenced by the IMF. We suggest this is a signature of the action of the IMF on CRs, which has a high frequency cut-off. However, this does not mean that, in special periods like Forbush decreases and periods around solar flares, changes of the spectra and some selective periodicities may not occur. Recently, Yasue et al. (1994) reported using the large portion of the data (1985-1991) from Matsushiro station (median energy 686 GV), that the power spectrum consists of three parts. The second one, with the power spectrum index close to -2.0, has a high frequency cut-off at $f \approx 8 \times 10^{-6}$ Hz. Above this frequency cut-off the spectral index is zero. Assuming 686 GV particles, the minimum time variations due to the IMF can be expected at 6×10^{-6} Hz, a value (i) which is very different from that observed as "cut-off" at NM energies, and (ii) which is not greatly different from that expected from T_{min}. This conclusion, however, must be assumed with some caution. In fact, the time series at Matsushiro are constructed from data with a total count rate of 2.1×10^4 per hour, while JJ NM data have the count rate 1.3×10^6 per hour and LS has 1.6×10^6 counts per hour. Thus, for clarifying this "frequency cut-off" more stations with different count rates at similar rigidity cut-offs as well as stations with similar count rates at different rigidity cut-offs should be checked.

Once the action of the IMF is assumed to be one of the dominant processes in the formation of CR fluctuations above 40 min, one can expect that the distribution of the IMF inhomogeneities described by the characteristics of the IMF time series will have some similarities if compared to CR fluctuations. Burlaga (1992) has shown that the IMF has multifractal scaling in the interval of 2-32 hours and that the lower cutoff (2 hours) is related to the use of hourly averages. The shape of scaling characterized by s(q) shown here is similar to that published in the mentioned paper (cf. Fig. 3 from Burlaga, 1992). One significant difference is in the values of s(q). For CRs the s(q) absolute value is much smaller than that for the IMF. This is not unexpected. Cosmic rays are flowing into the heliosphere from the interstellar region and their intensity is only slightly modulated (by some 10-15% during strong disturbances) by the IMF. Thus the modulation effect of the IMF is small in the absolute values of CRs and hence the small dynamics of the total flux of CRs measured by NMs. This fact can also explain the relatively small signature of multifractality in the data.

There are, however, other effects acting on the formation of CR time series recorded by NMs which influence their scaling properties. The most significant one is the diurnal variation. At higher energies this effect is not significant. However, at NM energies, the diurnal variation is a persistent, clear feature in the data. Thus a wide interval of scaling is not expected, and the scaling itself, if examined by the scaling exponent H, at times more than about 8 hours, is distorting the result. We have performed such an analysis on test data with $f^{-1.75}$ and random phases and simulated the diurnal variation by applying a slight signal of the proper periodicity. Depending on the amplitude of the additional periodical signal, a deviation from linearity of $\Delta I(n\tau)$ vs $n\tau$ in the log-log plot appeared, similar to that observed in Fig. 3 above $T > 6$-8 hours. Other additional effects which can influence the scaling are the atmospheric processes which are essentially of multifractal character (Tessier et al., 1993; Schmitt et al., 1993). The most significant of them is the effect of the variable total amount of material above the detector, taken into account in first approximation by barometric pressure correction.

7 Summary

We present the results of the first analysis of scaling properties of short time variations of CRs measured by NMs. The analysis has shown that the characteristics of time series at two NMs are similar for the same periods of observations, that scaling with unique characteristic is not observed in a wide interval of times, and that scaling itself is dependent on the level of interplanetary turbulence. Nevertheless the fractal description of the NM time series, as characterized by the scaling index H, or the yardstick length index L, can be useful in a systematization of CR fluctuations over different time scales and can be used as a complementary description of power spectrum analysis. Similarities in the power spectra and in the scaling of two closely situated NMs provide the potential for an extensive detailed study of the general characteristics of CR fluctuations below the diurnal periodicity (different cut-off rigidities, different levels of solar activity).

The analysis leads to more specific conclusions:

a. A high frequency cut-off in scaling is observed at approximately 20 min on both monitors and using the measurements with different time resolution. At times above 40-60 min and lower than 6 hours, where scaling is observed, the dimensionality of the process decreases with increasing interplanetary disturbance. The minimum time of 40-60 min agrees with the action of the IMF inhomogeneities on CRs at NM energies and confirms the importance of CR scattering on interplanetary turbulence. The multifractality seen in the data is not too pronounced because of the low dynamics of CR intensity variations.

b. For time < 20 min the general characteristic of the CR time series is similar to that of white noise, and no effect of the IMF is observed.

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