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ANALYSIS OF THE SMALL-SCALE COSMIC RAY FLUCTUATIONS SPECTRUM INFERRED FROM GROUND-BASED COSMIC RAY OBSERVATION DATA.

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RESUMEN

En el presente trabajo se estudian teóricamente las relaciones existentes entre las características espectrales de la intensidad de los rayos cósmicos y el campo magnético interplanetario, usando para esto las características espectrales de la intensidad de la radiación cósmica inferidas de datos observados en superficie. Se determinan las características espectrales medias del campo magnético interplanetario y los resultados se comparan con las observaciones. Se describen, así mismo, los resultados del análisis de las fluctuaciones en la intensidad de los rayos cósmicos durante varios periodos y para varias estaciones.

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ABSTRACT

The relationships between the spectral characteristics of cosmic ray intensity and interplanetary magnetic field are studied theoretically using the spectral cosmic ray intensity characteristics inferred from ground-based observation data. The mean spectral characteristics of interplanetary magnetic field are calculated. The results of the calculations are compared with observational results. The results of analyzing the cosmic ray fluctuations during various periods and at various stations are described.

INTRODUCTION

The cosmic ray propagation in interplanetary space gives rise to the characteristic fluctuations of the cosmic ray intensity due to the scattering of charged cosmic ray particles by random inhomogeneities of the interplanetary magnetic field.

Although particles of comparatively low energies can describe the largest fluctuations, the most important information is obtained from the study of the cosmic ray fluctuations in the medium and high energy ranges (above several GeV). The propagation of such particles is adequately described by the diffusion theory equations. The physical reason for this is that a particle with a large Larmor radius ($\rho = \frac{PC}{eH} \gg R_c$, where R_c is the correlation radius of random magnetic field) can "see" a broad spectrum of interplanetary magnetic field inhomogeneities, whereas low-energy particles interact with the high-frequency side of the magnetic inhomogeneity spectrum and carry information on a comparatively narrow range of the magnetic field turbulence. The smallness of the fluctuation amplitude in the high-energy range is compensated by the fact that ground-based observations, in this energy range, are made within a high statistical accuracy (Dorman and Libin, 1985; Dorman, 1982; Kozlov, 1981a; Dorman *et al.*, 1979, 1978).

SOFTWARE FOR STUDYING THE FLUCTUATIONS

To get a comprehensive analysis of the factors and processes that give rise to the generation, shaping and development of the observed fluctuations, one has to discriminate all the periodicities hidden in the incoming information, to trace their dynamic development, to reject all the inessential phenomena and events accompanying the cosmic ray fluctuations, and to find analytically, if possible, the relationships between the essential processes and events. In such an approach, not only the detailed calculations and estimation of the fluctuation spectra, which are useful and highly informative by themselves (see Gulinsky and Libin, 1979), but also the study of the behaviour of the fluctuation spectrum as a whole (*i.e.*, specifying the

analytical form of the spectrum, calculating its parameters, and comparing them with the various processes in the interplanetary space) are of great importance.

As shown by several spectral analysis studies (Bendat and Piersol, 1974, 1983; Max, 1983), the practical methods for estimating the spectra must encompass several stages including the preliminary analysis, the calculation of sampled correlations and spectral characteristics, and the interpretation of the obtained results. Figure 1 shows the flowchart for analyzing the cosmic ray fluctuations, the correlations between the fluctuations, and the reliability of the obtained estimates.

The data to be analyzed include the arrays of the results obtained by measuring the cosmic ray intensity with ground-based neutron monitors and scintillator telescopes and on board balloons and spacecrafts, $N_{ik}(t)$, and by measuring pressure P_{ik} and temperature T_{ik} ; the values of the coupling coefficients $W_{ik}(R)$; and the measured data of interplanetary magnetic fields B_{ik} (if such data are available). The optimum interval in the analysis is selected by introducing the frequency bands $f_1 \leq f \leq f_2$, where $f_1 \sim 10^{-5}$ Hz and $f_2 \sim 10^{-2}$ Hz for the fluctuations due to charged-particle scattering by random inhomogeneities of the interplanetary magnetic field; $f_1 \sim 10^{-7}$ Hz and $f_2 \sim 10^{-5}$ Hz for the fluctuations due to the sector structure of the interplanetary magnetic field and to the high-velocities fluxes.

The stationarity test is used to find out if the input data are feasible to be analyzed or else the input data arrays should be reduced to stationary or quasi-stationary form. In the test, the realization under study is broken into N equal intervals, whereupon the mean values and the variances of the data are calculated for each interval and the resultant chain of data is tested to find trends or other temporal variations that cannot be accounted only for the variability of the estimates due to sampling. The trends must be eliminated because they are extremely important when calculating the fluctuation power spectra. Variations with periods exceeding 12 hours contribute much to the amplitude of the high-frequency spectral estimates when analyzing small-scale variations of cosmic ray intensity. The results of simulating the process of power "pumping" to the high-frequency band (splitting of 1.15×10^{-5} Hz peak with a 0.4% amplitude was simulated) have shown that the contributions of the diurnal variation to the higher order harmonics are: $\sim 0.25\%$ for the semidiurnal variation and 0.1% for the 7-hour variation. In case of fluctuations with periods of several tens of minutes the contribution of the diurnal variation is hundredths of

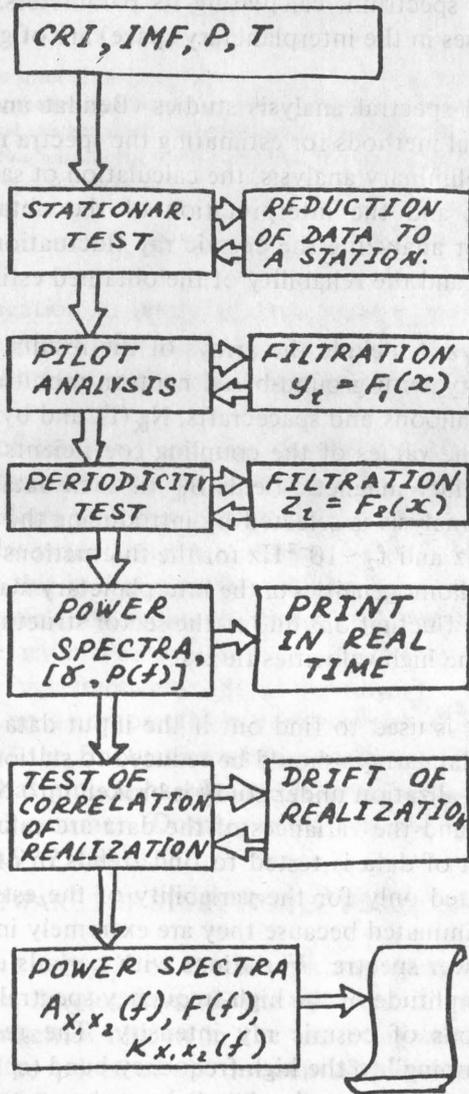


Fig. 1. Flowchart of the Fourier analysis of cosmic ray fluctuations.

one percent. Therefore, one has only to take into consideration that the amplitude of such fluctuations is of the same order. Since the band of the frequencies, corresponding to the fluctuations with periods smaller than several hours, is of major interest in the analysis, the allowance for such trends, which prove to be of long periods when solving our problem, is absolutely necessary. As to the splitting of the peaks at frequencies $f \sim 8 \times 10^{-5}$ Hz (with the amplitudes characteristic of the real processes), they fail to make, in any way, significant contributions to the higher order harmonics. The simulation of the splitting of the 1.8×10^{-4} Hz peak, with an amplitude of about 0.16%, gives rise to spurious peaks in the spectrum which do not exceed the 90% confidence interval in the $2 \times 10^{-4} \leq f \leq 1.66 \times 10^{-3}$ Hz frequency band. Figure 2a is an example of the spectral analysis of the function $\sin(t)$ (with an amplitude of 0.4% and a peak at 1.83×10^{-4} Hz) plus the white noise $\xi(t)$ (with an amplitude of $\sim 0.2\%$). As can be seen in the figure, except for the peak at the frequency 1.83×10^{-4} Hz, the form of the spectrum at all other frequencies is characteristic of white noise with a broad set of peaks falling below the 90% confidence

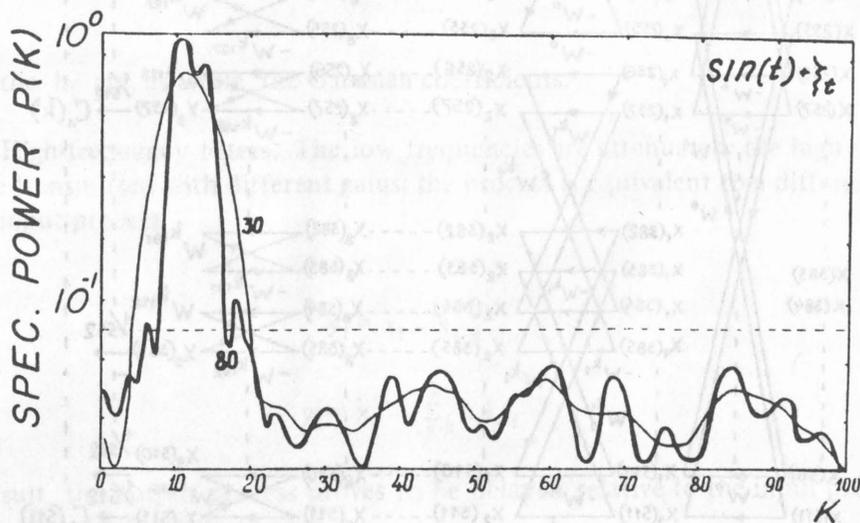
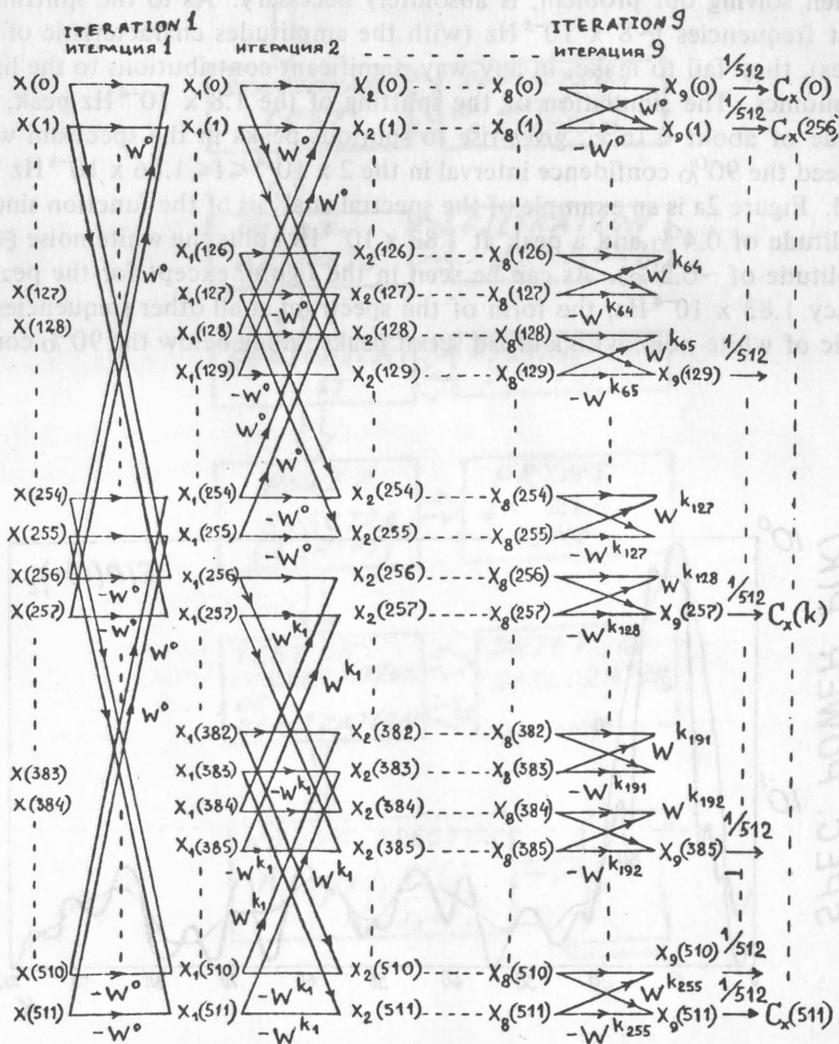


Fig. 2. (a) the fluctuation power spectra for various window widths (K is given in $1/60,000$ Hz). (b) Diagram for the realization of the fast Fourier transform for $N = 512$.

2(b)



level (dashed line). The observed peaks correspond to the fluctuations of the process with an amplitude of $\sim 0.2\%$ at all frequencies, which is dependent to a great degree on the white noise. The contributions of the function $\sin(t)$ to the higher-order harmonics is minimum and does not exceed 0.1% .

There exists a large number of filters used to eliminate high-frequency trends (Bendat and Piersol, 1974, 1983) of which the "first-difference" filters (Bode, 1945) proved to be the most convenient. The frequency characteristics, the gain factor, and the phase characteristics of the most extensively used filters may be found in (Bode, 1945).

The filters used in analyzing an input series fall into three categories:

(i) Low-frequency filters. The high frequencies are filtered out or attenuated; the low frequencies are transmitted with different gains; the filters correspond to an integration or smoothing of the input process (Bode, 1945).

$$y_t = \frac{1}{2k+1} \sum_{i=-k}^k h_i x_{t-i}$$

where the h_i are, as a rule, the Gaussian coefficients.

(ii) High-frequency filters. The low frequencies are attenuated; the high frequencies are transmitted with different gains; the process is equivalent to a differentiation of the input process

$$y_t = x_t - x_{t-1}$$

$$y_t = x_t - \sum_{i=-k}^k h_i x_{t-i}$$

As a result, the output process proves to be delayed relative to the input (a positive phase shift is introduced).

(iii) Resonance filters corresponding to an oscillating system tuned

nance frequency. The best resonance filter is the "multiple autocorrelation conversion" (Dorman and Libin, 1985, 1978) which consists in N-multiple application of the correlation conversion first to the input process and then to the correlation functions of higher orders

$$C_{xx}^{(n)}(\tau) = 2 \left(\frac{A_1}{2} \right)^{2n} \left\{ \cos 2\pi f_1 t + \sum_{j=2}^k a_j^{2n} \cos 2\pi f_j t \right\}$$

Where τ is the shift; A_1 is the amplitude of the maximum harmonic; a_j is the amplitude of rest harmonics. The filter is so adjusted that it is always tuned to the maximum frequency. By gradual filtering-out of the maximum frequency from the input series, one may obtain the values of the power at practically all the discriminated frequencies.

(iv) Filters resulting from the operations of summation and subtraction with appropriate delays. Such filters are sufficiently simple and applied to the cases where the fluctuations in the process under study must be correctly estimated by a trial analysis.

The trail analysis consists in the decomposition of the total sum of squared deviations $\sum_{t=1}^N (x_t - \bar{x})^2$ into the terms which contribute to the sum due to the variability of the input process with periods multiple to $T/2$, $T/4$ and $T/8$ of the studied period (T). The trail analysis makes it possible to synthesize the frequency characteristics of a filter to within a sufficient accuracy. Since such an analysis is easy to carry out without using computers, it has to be made in view of finding out what kind of information is contained in the spectrum and as an introductory part to the spectral analysis.

The one-dimensional spectral analysis consists in calculating sample estimates of the covariance function of the input process $C_{xx}(k)$ and spectral density $C_{xx}(f)$ for a certain interval of the observation data discretization and various correlation windows with cutoff point. Thus, the one-dimensional spectral analysis reduces to calculating the spectra of the fluctuation power of the input data arrays (the Fourier transform of the covariance or correlation function of the input process) with subsequent interpretation.

The visual inspection of the spectra calculated with different window frequency bands (widths) allows one to learn about the shape of the spectrum either by sim-

plifying it or reducing it to a more significant detail. Fig. 2a shows the power spectra for two values of the window width L (the numerals at the curves). It can be seen that oversmoothed estimates (in the terminology adopted by Bendat and Piersol (1983)) are obtained with $L = 30$, whereas a number of fine structures of the spectral characteristics, in particular a peak at $K = 68$, can be seen as the window frequency band increases up to $L = 80$. Without a visual control of the spectra it might be tempting to conclude that this peak was real; however, an increase of the frequency band of the window may lead to spectrum irregularities, which makes the calculations quite senseless. A reasonable compromise makes it possible to stop contracting the window in due time if one remembers that as the frequency band is tightened, the sampled spectral estimate becomes a polynomial of high degree in $\cos 2\pi f$ and hence it is easy to produce spurious peaks (Jenkins and Watts, 1972). Nevertheless, the window tightening is very important when finding the details of the spectrum, especially when it is made of windows differing significantly in their characteristics. Such an approach makes it possible to remove peaks which are due only to the procedure of the spectral parameter calculations because such peaks will be observed at different frequencies for different windows. The spectral analysis needs the use of correlational or spectral windows (weight functions). In this case their applicability scopes must be rigorously differentiated. The correlational windows are used directly in the temporal domain, and the spectral wave functions (the Fourier transform of the appropriate wave function) only in estimating the spectra.

The cosmic ray fluctuations were analyzed using the Cooley-Tukey, Gauss, Tukey-Hanning, Parzen and Tukey windows, out of which the Tukey and Parzen functions proved as a rule to be the most suitable because the least correlation of the adjoining bands and the least power "leakage" from one estimate to another. The application of different spectral windows is especially important when identifying and interpreting the spectra obtained. As was shown by Bendat and Piersol (1974) and Jenkins and Watts (1972), the interpretation of the obtained results reduces to the visual study of the spectra calculated with decreasing window frequency bands. The interpretation is much assisted by the program periodicity test which consists in examining the autocovariance functions, the spectral densities, the trial analysis results, and the physical considerations concerning the nature of the spectra. The periodicity test is in fact the initial stage of the preparation for carrying out the two-dimensional analysis.

When several descriptions are applied to the same process, or else the problem of

correlation between various input data arrays has to be specified, one is to use the realization correlation test which reduces to calculating the cross-correlation functions, the cross-correlation coefficients, and the coherence spectrum (Jenkins and Watts, 1972).

Joint spectral analysis. Since the cosmic ray fluctuations are of the same nature for the particle fluxes of the same energies detected with different instruments, it is suitable to carry out a joint analysis of the cosmic ray intensity data or of the intensity and parameters of the interplanetary magnetic field. Such a procedure makes it possible to get a much more reliable identification of the true peaks in the spectra, whereas the spurious peaks associated with methodical errors will be essentially different; therefore, their contribution to the joint spectra will be largely suppressed. Besides that, certain conclusions concerning the nature of the observed fluctuations can be drawn from the joint analysis of the intensities of cosmic rays and interplanetary magnetic field. The joint spectral analysis is used to calculate the sampled estimates of the mutual covariance function and the estimates of the estimates of the cospectrum L_{xy} and the quadrature spectrum Q_{xy} (Bode, 1945) which makes it possible to estimate the mutual amplitude spectrum A_{xy} , the phase spectrum P_{xy} , and the coherence spectrum C_{xy} (Jenkins and Watts, 1972; Max, 1983).

It is very important in the analysis to estimate the delays between the studied data arrays. The simplest preliminary estimation consists in the centering of the mutual covariance function C_{xy} which means the shifting of one of the data series with respect to the other until the C_{xy} maximum corresponds to the zero value of "K".

The necessity of further levelling of the delays between the input data series is verified when calculating the phase spectrum and the coherence spectrum.

The above described flow chart for calculating the spectral characteristics of cosmic ray fluctuations is not obligatory. It is the particular needs of the study that are to count, but the experience of its application to studying cosmic ray fluctuations has demonstrated sufficient effectiveness and flexibility (Dorman and Libin, 1985). The flow chart has been realized in the form of several programs. It should be noted that each of the program segments was realized as subroutines, so all the programs were largely overlapped.

THE ALGORITHM FOR FAST FOURIER TRANSFORM IN REAL-TIME CALCULATIONS

According to Bendat and Piersol (1974, 1983), the equation describing the discrete Fourier transform for the series $X(m)$ may be written as

$$C_x(k) = \frac{1}{N} \sum_{m=0}^{n-1} X(m) W^{km}, \quad k = 0, 1, \dots, N-1,$$

where $W = e^{-i2\pi/N}$

The Cooley-Tukey algorithm is based on the assumption that $N = 2^n$, $n = 1, 2, \dots, n_{\max}$ (Jenkins and Watts, 1972). The generality is not lost if the length of the series N is chosen to be sufficient for the neutron component intensity (multiplicity) fluctuations of given periods to be studied. In particular, for the fluctuations with periods of about 30 min (a 5-min detection interval) and about 0.5 and 1 day (a 1-hour detection interval) it is sufficient to choose $N = 512$.

When presented in binary form, the expressions of indices k in the $C_x(k)$ coefficients appear in inverted order, opposite to the expressions of indices m in $X(m)$ where they appear in natural order. The binary inversion at $N = 2^n$, which is much computer time-consuming in the general case, may be realized effectively if the data transposition method is used.

The input data array can be converted into the complex form at $I_m = 0$ considering that the detected cosmic ray intensities have the format of integers and the algorithm to be realized uses the complex form of the representation of numbers.

Thus, the procedure which realizes the Cooley-Tukey algorithm for calculating the fast Fourier transform may be outlined as follows.

(i) The use of the data transposition method to obtain the inverted sequence K_s from the series M_s presented in the natural order

$$M_s = N/2^s \quad \text{at} \quad s = 1, 2, \dots, n$$

where $n = \log_2 N$.

(ii) Derivation of the sequence of powers of W , where the power-law exponents form the sequence of K obtained by binary inversion from the series M_s :

$$\{W^{k_s}\} = W^{k_0}, W^{k_1}, W^{k_2}, \dots, W^{k_{n/n-1}}$$

(iii) Conversion of the integer data array stored in the buffer into complex form; the real part of the complex number R_e is presented in the format with floating point in two cells of the buffer and the imaginary part $I_m = 0$ is stored in the next two cells of the data buffer.

(iv) Consistent execution of the $n = \log_2 N = 9$ iterations according to the diagram shown in Fig. 2b. Each group to the i -th iteration is in correspondence with its factor W^{k_s} from the sequence W^{k_s} . The intermediate values obtained after the i -th iteration are written instead of the input array $X(m)$. As seen in the diagram, this approach is quite realizable with the iteration method for realizing the discrete Fourier transform algorithm and makes it possible to save computer memory.

(v) Calculations of the $C_x(k)$ coefficients. The fast transform calculation procedure described above is organized to be an interval subroutine of the segment* which not only works as described above but also operates with management data transceiver and with disk files. The subroutine is reiterable, thereby permitting the segment to function under the management of a real-time disresident program dispatcher with the user-controlled invoked interval.

The algorithm described above is program-realized in MNEMOKOD language of the ASPO operational system which has made it possible to significantly save the memory and program execution time. The estimates for $N = 1024$, $N = 512$ and $N = 256$ (N is the length of the buffer filled by the input series) have shown that the program operates $\sim 2N$ cells of main memory for processing the data array presented in complex form and $\sim N$ cells for the data transposition and calculations of the powers of W . Thus, the given realization of the Cooley-Tukey algorithm requires $3N$ cells of main memory.

* To save main memory, the program module is organized as a segmented job to include not only the fast Fourier transform calculations program but also a complex of programs for statistical and spectral processing of intensities and multiplicities.

METHODS FOR ESTIMATING THE COSMIC RAY FLUCTUATIONS

Despite the long history of estimating various spectra from time series, the classical methods cannot be applied directly to the studied phenomenon because of its specific features. The first feature of the problem is that the statistical characteristics of the process not only exhibit regular trends (which may in principle be removed by various filtering methods) but also change significantly during periods most interesting physically (for example, during Forbush decreases), that is to say, the process gets non-stationary. In this case, the very notion of the spectrum is not defined and the periodogram-based classical transformation and its modifications (the fast Fourier transform, the Blackman-Tukey method, etc.) get invalid. The technique used conventionally in such a situation, *i.e.* the discrimination of quasi-stationary intervals (which is difficult by itself), is faced with the following difficulties. Such intervals (if any at all) may prove to be very short. At the same time, the Fourier method is known to yield poor results and cannot discriminate similar frequencies with small data arrays, whereas the second feature of the problem is that it just needs the discrimination of similar frequencies every of which may be relevant to certain processes in the circumsolar space. The so called auto-regression methods have been used since recently to separate the frequencies into short and long modes. The essence of the methods is to introduce the supplementary assumption that the studied process can be described by an auto-regressive model

$$X_{t+1} = \sum_{i=0}^p a_{i+1} X_{t-i}, \quad t = 0, 1, 2, \dots \quad (1)$$

of the order p which is known in advance. The assumption is used to estimate, by one or another method, the auto-regression coefficients and to select the best (in a sense) order. After that, the coefficients are used to calculate the spectrum unambiguously. Such an approach has also been realized in the described method using various algorithms (of the type of Burg, Levinson-Durbin, Pisarenko and Proni, and their modifications). The approach has yielded satisfactory results in several cases but proved to be inapplicable to the essentially non-stationary events.

We proposed the following approach to overcome the difficulties. The process was assumed to be describable by an auto-regressive model in which the coefficients themselves are time-variable:

$$X_{t+1} = \sum_{i=0}^p a_{i+1}(t) X_{t-i}, \quad t = 0, 1, 2, \dots \quad (2)$$

Obviously, such a process is not stationary. Each coefficient is presented to be a series in a certain given complete set of functions $\{\varphi_k\}$

$$a_i(t) = \sum_{k=1}^N C_{ik} \varphi_k(t) \quad (3)$$

with unknown coefficients C_k . In particular, the power-low series $\{1, x, x^2, \dots\}$ may be chosen to be the set of functions. After that, the least-squares method is used to calculate the coefficients C_k for the selected number of terms N of the expansion (3) and order p of the model (2). The model-order p and the number of terms N in the expansion (3) may be selected to be in a sense optimal. Such an approach permits the concept of instantaneous spectrum to be introduced for an unsteady-state process.

At each moment t^* the estimated parameters C_{ik} correspond to an auto-regressive model whose constant coefficients are known:

$$a_i(t^*) = \sum_{k=1}^N C_{ik} \varphi_k(t^*) \quad (4)$$

Such a process will be thought as stopped at moment t^* (it may be continued to infinity). The process is stationary and corresponds to a certain spectrum which is calculated analytically using these coefficients. The spectrum of the process stopped at the moment t^* will be called the t^* -instantaneous spectrum of the studied process.

Arranging the sequence of instantaneous spectra with respect to t , one obtains a dynamical picture of the reconstructed non-stationary process.

The discussed technique realizes all the approaches described above, the direct Fourier transform and its modifications, the auto-regressive models, and the instantaneous spectra. Depending on particular situations, various combinations of these approaches may be used, thereby making it possible to study the time series more rigorously and to control the results obtained.

The above mentioned methods have been used to design a data processing system for the unified-series computers in which some auxiliary routines were also realized by filtering the high and low frequencies, excluding the regular variations, estimating the process dissonance (*i.e.*, appearance of nonstationarity), and calculating the basic steady characteristics of the process. The computer-realized data processing system met the following requirements:

1. Extended dialogue with the user.
2. The feasibility of data processing with different media.
3. The feasibility to create and build up the data band.
4. Easy access to any data segment.
5. Presentation of results in a visual graphic form; in particular, construction of a dynamic pattern of the process spectrum rearrangement.

EXPERIMENTAL OBSERVATIONS (ESTIMATES OF SPECTRAL SLOPES)

Five-minute and hourly values of the cosmic ray intensities at Moscow, Utrecht (September 7-24, 1977), and Kerguelen (September 18-19, 1977) neutron monitors were used to calculate the cosmic ray fluctuation power spectra in the frequency band $5 \times 10^{-6} \leq f \leq 1.66 \times 10^{-3}$ Hz. The reliability of the estimates obtained was verified using the spectra window contraction method (for the Tukey and Parzen windows) and the calculations of the mutual spectra between pairs of stations on the one band and each of three sections of the neutron monitor at Kerguelen on the other. The analysis was carried out in the high-frequency range (search for peaks and their dynamic evolution) and in the low-frequency range (estimation of the spectral slope behavior at the frequencies $f \leq 2 \times 10^{-4}$ Hz). The spectra were specified in the parametric form $P(f) \sim Af^{-\gamma}$, where f is the frequency and γ is the spectral index.

The spectra in the low-frequency range were studied using the cosmic ray neutron component intensity data from Vostok (Antartica) for 1979, from Lomnický Stit for 1979, and from Baksan for 1982 and the IZMIRAN scintillation supertelescope data for 1978-1983. Fig. 3 (a-c) shows the cosmic ray fluctuation power spectrum inferred from the Moscow neutron monitor data for December 1-10, 1982. The spectra were estimated on the basis of daily intervals in each three hours. The behaviour of the spectra as the whole and the estimates of their slope dynamics have convincingly demonstrated the rise of γ from 1.5 to 2.9-3.2 before the December 8, 1982 flare (Fig. 3d). The same rise of the spectral index (though with a smaller amplitude) observed at 1330 UT on December 2, 1982 is probably due to the anomalous value of the diurnal variation on December 1-2, 1982 (Fig. 3b). Another effect seen clearly in the figures should be noted, namely, the opposite behaviour of the spectrum in the frequency band $f \geq 7 \times 10^{-3}$ Hz. Before the occurrence of interplanetary medium disturbances, the low-frequency side of the spectrum gets steeper,

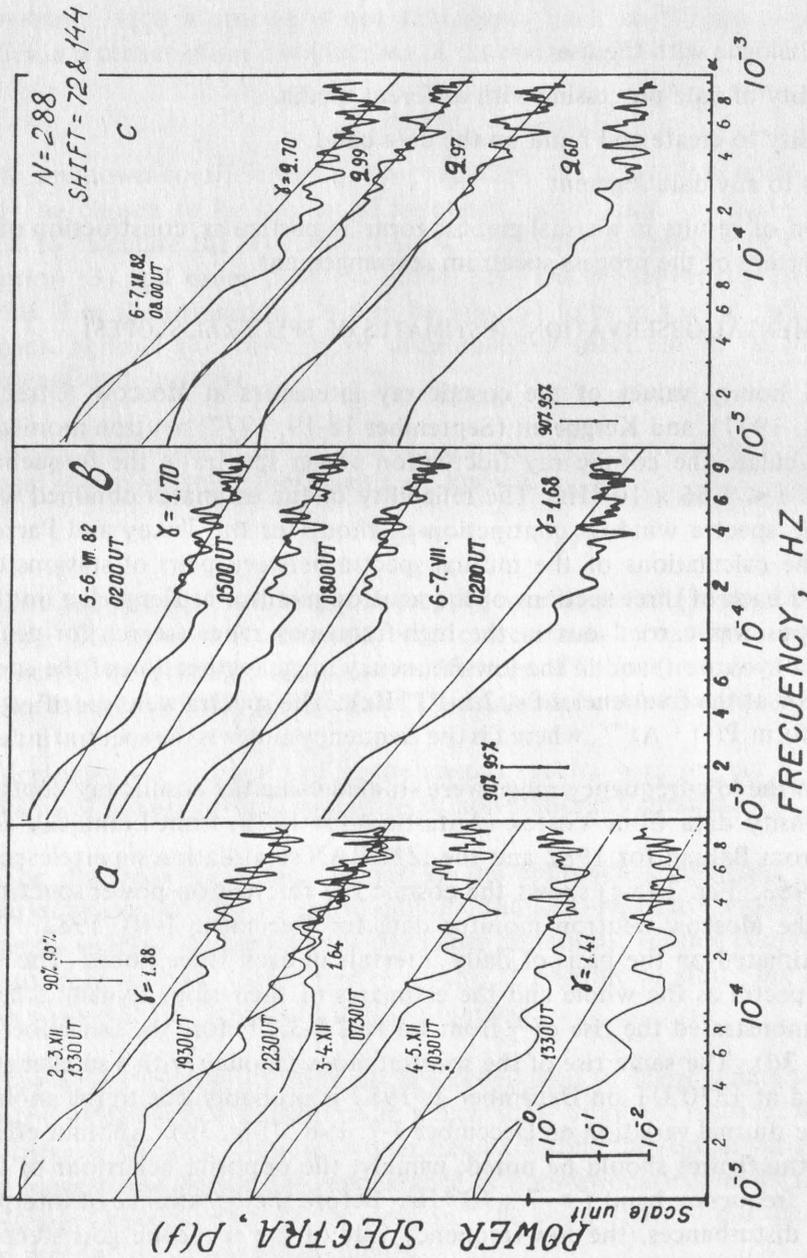
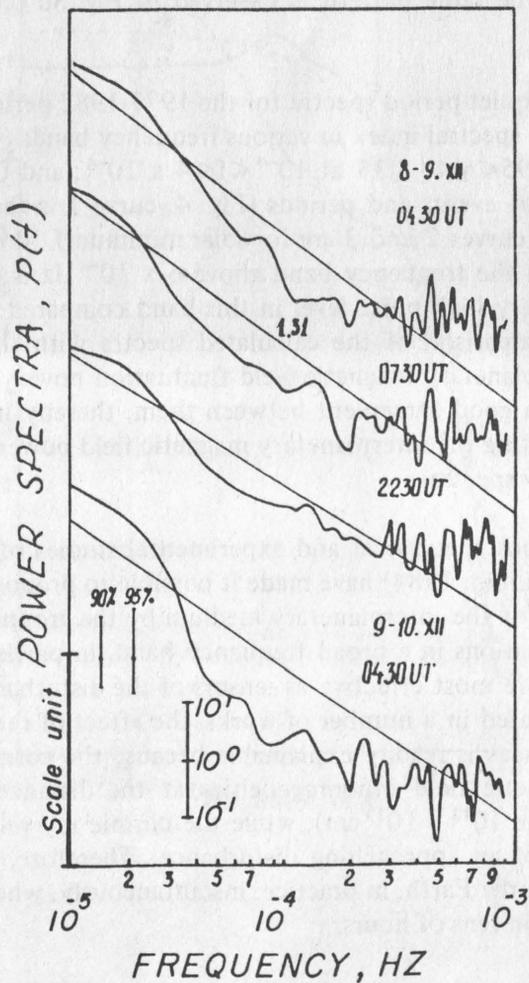


Fig. 3. The fluctuation power spectra of the cosmic ray neutron component intensity for the period December 1-10, 1982.

3(d)



i.e. the spectral index rises from $-1.0 - -1.2$ up to $-2.0 - -3.8$ and in the $f > 10^{-3}$ Hz side rises from $-0.2 - -1.0$ up to positive values. This effect found firstly by Kozlov (1984) in the high-frequency band and by Libin (1983) in the low-frequency band was called the "butterfly" effect because the wings of the spectrum "flap" before disturbances. The same pattern is observed in Fig. 3d (curve 1, 0800 UT on December 6, 1982).

The study of the quiet-period spectra for the 1977-1982 period has demonstrated the variations of the spectral index in various frequency bands ($-1.45 \leq \gamma \leq -1.75$ at $f \leq 3 \times 10^{-6}$ Hz; $-1.95 \leq \gamma \leq -3.35$ at $10^{-4} \leq f \leq 4 \times 10^{-6}$; and $0.55 \leq \gamma \leq 2.10$ at $f \geq 10^{-4}$ Hz) for different events and periods (Fig. 4, curve 1 is the matched spectrum for solar maximum, curves 2 and 3 are for solar minimum). It should be noted that the spectral index in the frequency band above 6×10^{-4} Hz is very difficult to estimate because of a very high noise level in this band compared with the fluctuation amplitudes. The comparison of the calculated spectra with the available identical spectra of the interplanetary magnetic field fluctuation power (Fig. 5) in the same periods has shown a good agreement between them, thereby indirectly confirming the results of calculating the interplanetary magnetic field power spectra through the analogous cosmic ray spectra.

Thus, the numerous theoretical and experimental studies of cosmic ray fluctuations (Dorman and Libin, 1984) have made it possible to propose the techniques for estimating the state of the interplanetary medium by the ground-based observations of cosmic ray fluctuations in a broad frequency band, in particular the 20-420 min fluctuations which are most effective as sensors of the disturbances approaching the Earth. As was indicated in a number of works, the effect of the cosmic ray advance relative to disturbances is readily explainable because the cosmic rays perceive the interplanetary magnetic field inhomogeneities at the distances of their transport scattering path (some $10^{12} - 10^{13}$ cm), while the cosmic ray velocity is almost three times the velocity of an approaching disturbance. Therefore, the cosmic rays will bring information to the Earth, in practice, instantaneously, whereas the disturbance will reach the Earth in tens of hours.

Because of a wide-energy range of cosmic rays detected on the Earth, the distances between the Earth and the approaching magnetic disturbances may prove to be very different. By detecting particles of different energies, it is possible to find the inhomogeneities at distances of up to several A.U.. It should be noted once

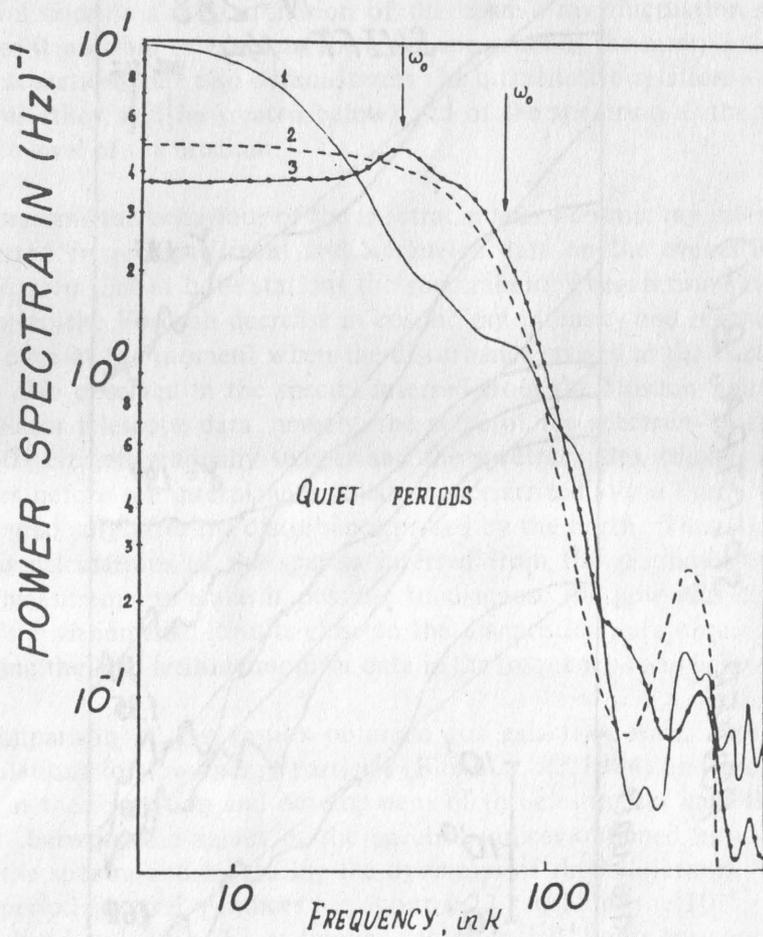


Fig. 4. The fluctuation power spectra of cosmic rays during quiet periods around solar maximum (curve 1) and around solar minimum (curves 2 and 3). Frequency in 1/60,000 Hz.

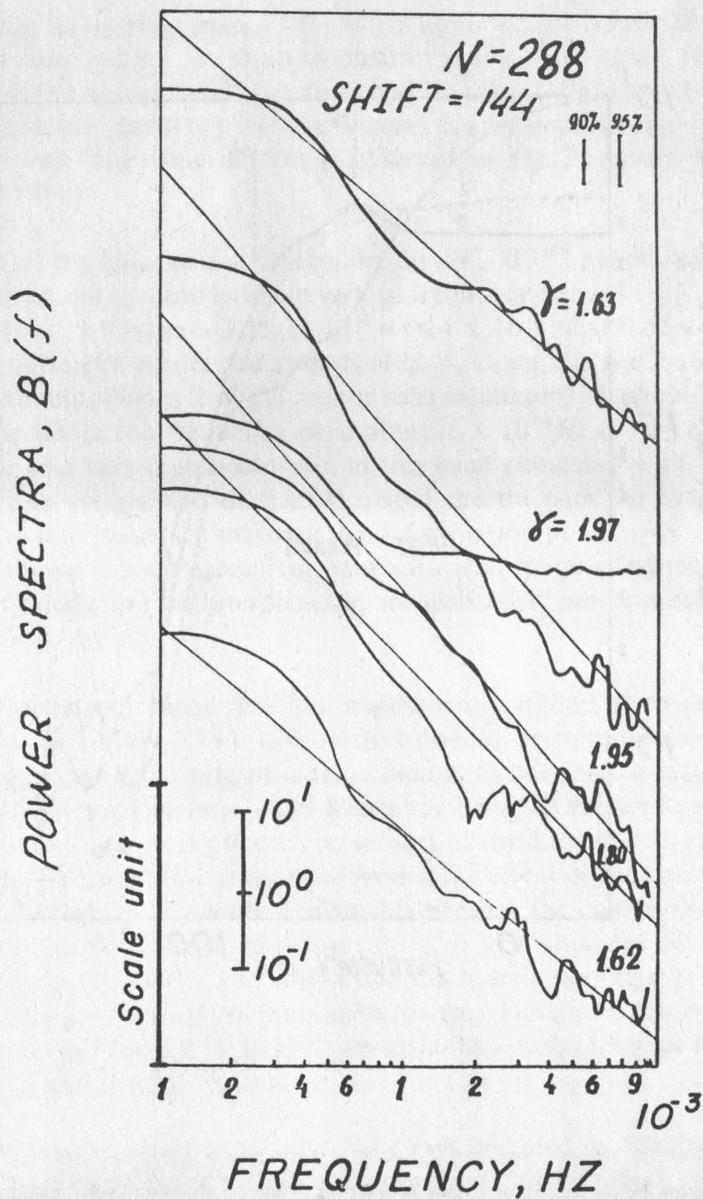


Fig. 5. The power spectra of the interplanetary magnetic field fluctuations during December, 1982.

again that the potentialities open up by studying the fluctuations are not exhausted at this level because the examination of the cosmic ray fluctuation spectrum not only makes it possible to estimate the mean spectrum of the interplanetary magnetic field fluctuations but also demonstrates the quantitative relationship of isolated fluctuations (they will be treated below) and of the spectrum as the whole to the disturbance level of the medium.

Fig. 6 presents the behaviour of the spectral index of cosmic ray intensity fluctuations inferred from the Utrecht and Kerguelen data on the events in September 1977. It is seen that at both stations the spectral index began rising at least 12 - 16 hours prior to the Forbush decrease in cosmic ray intensity and reached its maximum in practice at the moment when the disturbance arrived at the Earth. The same pattern is also observed in the spectra inferred from the Moscow neutron monitor and scintillator telescope data, namely, the slope of the spectrum in the frequency band $f \leq 10^{-5}$ Hz gets gradually steeper and the spectral index reaches its maximum three hours before the interplanetary disturbance arrived at the Earth, whereupon it decreased gradually after the disturbance passed by the Earth. Thus, the regular and continuous calculations of the spectra inferred from the ground-based cosmic ray intensity measurements make it possible to diagnose the powerful disturbances in the Earth's environment. Results close to the diagnostics were obtained by Kozlov (1981) using the high-latitude monitor data in the frequency band below 5×10^{-4} Hz.

The comparison of the results obtained for galactic cosmic rays with analogous calculations for low-energy particles (Blokh *et al.*, 1984) and the study of the dynamics in the formation and development of three estimates have shown a good agreement, between the values of the spectral indices obtained by identifying the slopes of the spectra and by tracing the dynamics of their variations. In both cases the quiet-period spectral γ indices are about 1.73 ± 0.15 in the $10^{-4} - 2 \times 10^{-3}$ Hz frequency band and 3.1 ± 0.3 at frequencies above 10^{-4} Hz, in very good agreement with the field measurement-results. During the same periods (November and December, 1977), the spectral index of the interplanetary magnetic field power was about 1.85 ± 0.35 in the frequency band $10^{-2} \leq f \leq 3 \times 10^{-4}$ Hz. The values obtained are close to the results of the earlier works of the Japanese groups where the data of a balloonborne 4 m^2 plastic scintillator were used to estimate the spectral indices which proved to be $\gamma = 1.7$ in 1972 and $\gamma = 2.1$ in 1975 for the $3 \times 10^{-4} \leq f \leq 10^{-2}$ Hz frequency band.

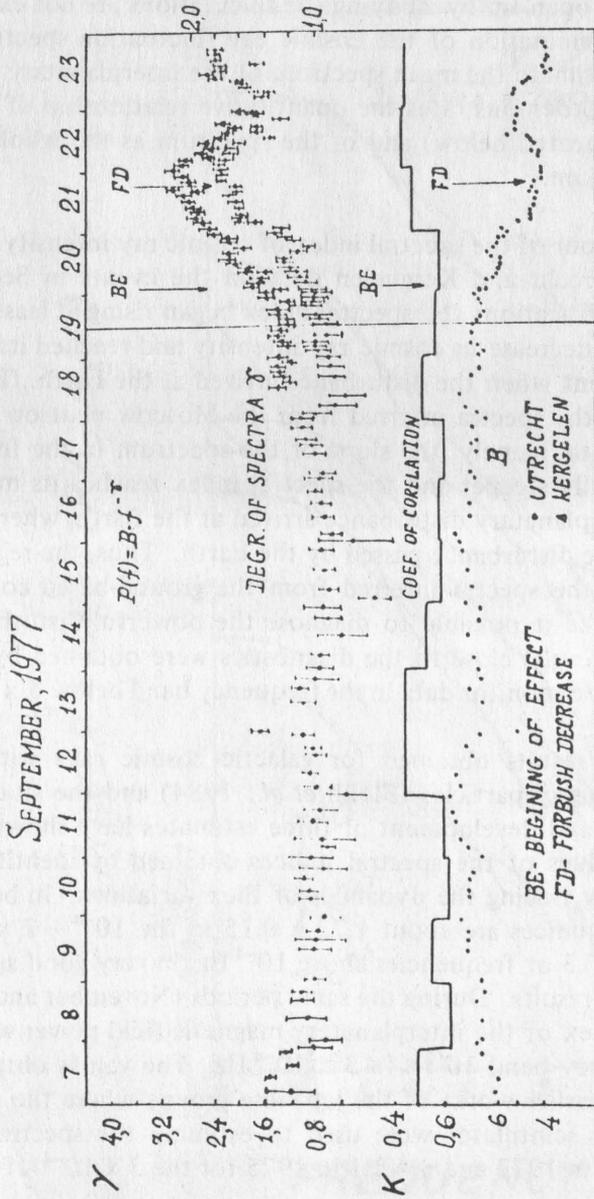


Fig. 6. The behaviour of the spectral index γ of the cosmic ray fluctuation spectrum before and after the interplanetary disturbances reach the Earth.

EXPERIMENTAL OBSERVATIONS (SPECTRAL LINES)

Not only cosmic ray fluctuation spectra in a broad frequency band as the whole but also the behaviour of individual spectral lines (peaks) during various periods of solar, interplanetary, and geomagnetic activity are very important to study. The selected period of September 7 - 23, 1977 was analyzed using the 5-min cosmic ray neutron component intensity data from the cosmic ray stations at Utrecht (middle latitude) and Kerguelen (high latitude). The analysis was carried out by the power spectrum method, the auto-regressive methods, and the method described above using the 12-hour and 24-hour intervals with a 3-hour shift. In such a way, more than a hundred dynamic spectra were obtained which permit to estimate the dynamical behaviour of the spectral characteristics throughout the entire studied range.

The September 7- 23, 1977 period is characterized by several solar flares which occurred from September 9 to 22, namely, on September 7 at 2227 UT (class 1B at $10^{\circ}\text{N } 90^{\circ}\text{E}$), 2252 UT (2N at $10^{\circ}\text{N } 90^{\circ}\text{E}$) and 2255 UT (1N at $9^{\circ}\text{N } 90^{\circ}\text{E}$); on September 9 at 1646 UT (2B at $10^{\circ}\text{N } 80^{\circ}\text{E}$); on September 14 at 1545 UT (1N at $6^{\circ}\text{N } 7^{\circ}\text{E}$); on September 16 at 2230 UT (3N at $8^{\circ}\text{N } 19^{\circ}\text{W}$); on September 18 at 0050 UT (2N at $7^{\circ}\text{N } 33^{\circ}\text{W}$); on September 19 at 1045 UT (3B at $9^{\circ}\text{N } 49^{\circ}\text{W}$); on September 20 at 0321 UT (3N at $15^{\circ}\text{N } 55^{\circ}\text{W}$). Forbush decreases were observed in cosmic rays on September 12 (2% amplitude) and on the 21st (5 - 6%). A persistent ionospheric storm was observed from the 19th.

A weak geomagnetic storm was recorded on September 13-14, and a strong geomagnetic storm was observed against a flare-generated recurrent background on September 19-23. Nevertheless, all this flare-induced activity was explicitly reflected in cosmic rays only on September 12 and 21. This is why the analyzed interval was tentatively broken into three parts, namely, the quiet periods (September 8 - 9 and 15 - 19), the periods before the Forbush decreases (September 10 - 11 and 19 - 20), and the periods of the Forbush decreases.

Fig. 7 presents the cosmic ray fluctuation power spectra on September 8 and 9, 1977 inferred from the diurnal realizations (the auto-covariance functions are characterized by small amplitudes and, simultaneously, a significant discreteness of the lines, Fig. 7a). The spectra are characterized by a weak frequency dependence (Fig. 7b). The auto-regressive models confirm the results of the Fourier analysis in that

the auto-regression estimation of the power spectrum has failed to show specific peaks in the spectra falling outside the 95% confidence interval. The study of all the quiet (or quiescent)-period spectra has demonstrated the almost absolute absence of significant ($\geq 95\%$) peaks, a low power level of the estimate in the high-frequency band ($f \sim 3.3 \times 10^{-4}$ Hz) throughout the studied range, and a relatively low value of the spectral index γ . These features are reliably traced not only in the results of the present work but also in the studied spectra for other periods (Libin, 1983a; Gulinsky *et al.*, 1983).

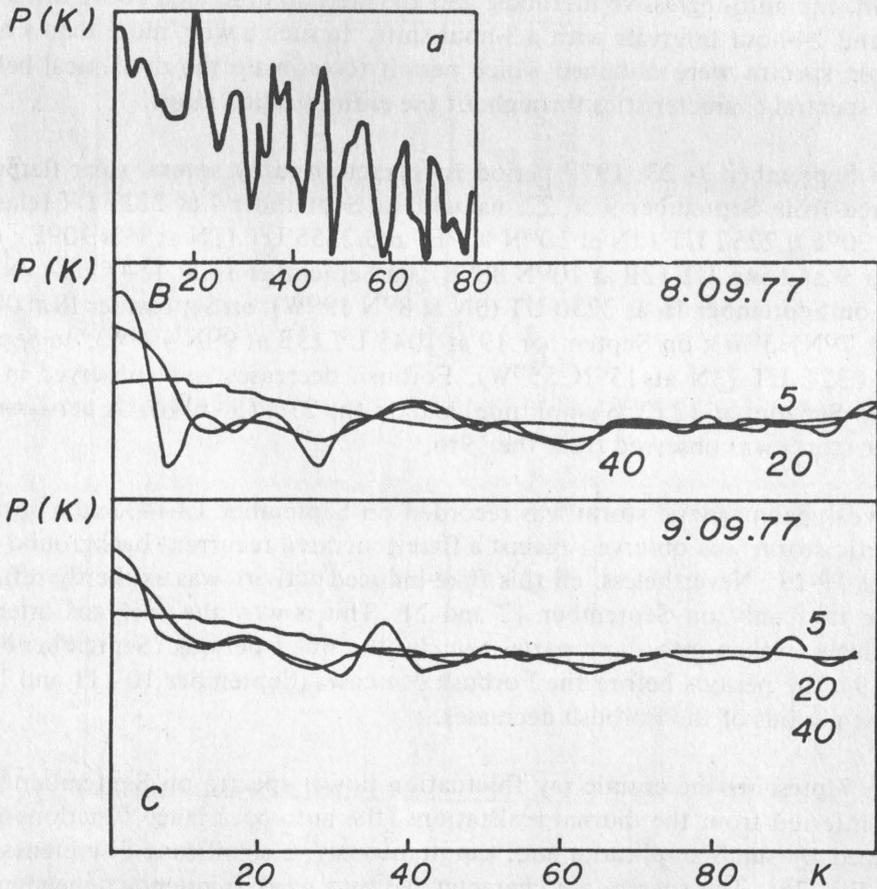


Fig. 7. Autocovariance function (a) and the cosmic ray fluctuation spectra (b, c) on September 8 - 9, 1977.

The analysis of the spectra calculated for the periods before the interplanetary medium disturbances in the Earth's vicinity has revealed a complicated and varying pattern of the occurrence and formation of the quasiperiodic fluctuations of the cosmic ray particle flux intensity on the Earth's surface and at different altitudes. The complicated and varying pattern is traced especially well in calculating the instantaneous spectra in terms of the auto-regressive models of order 10 and 20 (Fig. 8).

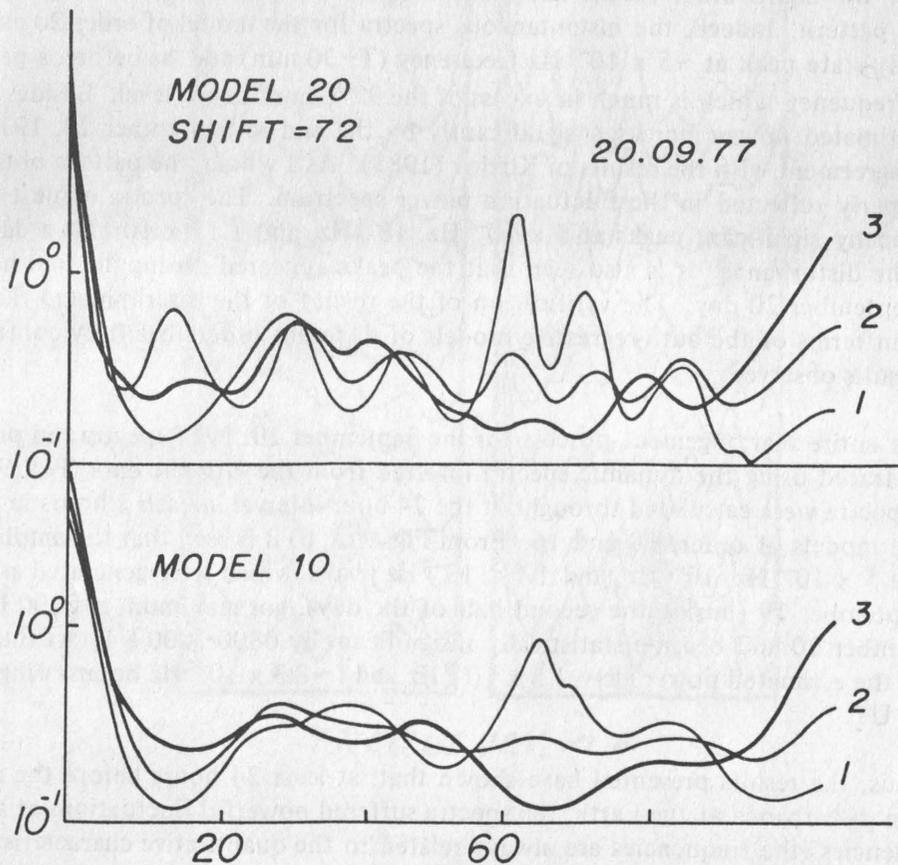


Fig. 8. The instantaneous spectra for periods prior to the arrival of interplanetary disturbances at the Earth.

The figure presents the instantaneous spectra at 0600 UT, 1100 UT, and 2000 UT on September 20, 1977 (curves 1, 2, and 3). The analysis of the spectra calculated has shown that, according to the oversmoothed estimates (Fig. 8, model order 10), a peak at 10^{-3} Hz frequency ($T \sim 15$ min) appeared practically within 20 hours prior to the Forbush decrease (September 21, 1977), whereupon it disappeared gradually and completely by the end of the day, while the power at $f \geq 1.5 \times 10^{-3}$ Hz increased simultaneously with the disappearance of the peak. At the same time, the application of the higher-order model has made it possible to detail significantly the observed pattern. Indeed, the instantaneous spectra for the model of order 20 exhibit a steady-state peak at $\sim 5 \times 10^{-4}$ Hz frequency ($T \sim 30$ min) and, as before, a peak at 10^{-3} frequency which is much in excess of the 99% confidence level. Besides that, the estimated power increased significantly by the end of September 20, 1977, in good agreement with the results of Kozlov (1981). As a whole, the pattern obtained is properly reflected in the fluctuation power spectrum. The spectra exhibit three statistically significant peaks at 5×10^{-4} Hz, 10^{-3} Hz, and 1.17×10^{-3} Hz a day before the disturbance. It is also seen that the peaks appeared during the first half of the September 20 day. The verification of the reality of the discriminated fluctuations in terms of the auto-regressive models of different orders has fully confirmed the results observed.

The entire rearrangement process for the September 20, 1977 spectra can properly be traced using the dynamic spectra inferred from the Utrecht data (Fig. 9a, b). The spectra were calculated throughout the 24-hour interval in each 2 hours in terms of the models of orders 10 and 16. From Fig. 9 (a, b) it is seen that the amplitudes of the 5×10^{-4} Hz, 10^{-3} Hz, and 1.7×10^{-3} Hz peaks, which were generated as early as September 19 (during the second half of the day), got maximum at 0200 UT on September 20 and became statistically insignificant by 0800-1000 UT. At the same time, the estimated power at $f \sim 1.3 \times 10^{-3}$ Hz and $f \sim 8.3 \times 10^{-4}$ Hz began rising from 2000 UT.

Thus, the results presented have shown that, at least 24 hours before the arrival of the disturbance at the Earth, the spectra suffered powerful fluctuations at several frequencies (the frequencies are always related to the quantitative characteristics of the disturbance) which exceeded the 95% confidence level and dissipated to the low- and high-frequency bands prior to the arrival of the disturbance. The analysis of the same period but on the basis of 12-hour (instead of 24-hour) intervals has properly confirmed earlier results. From the calculations it is seen that the clearly ex-

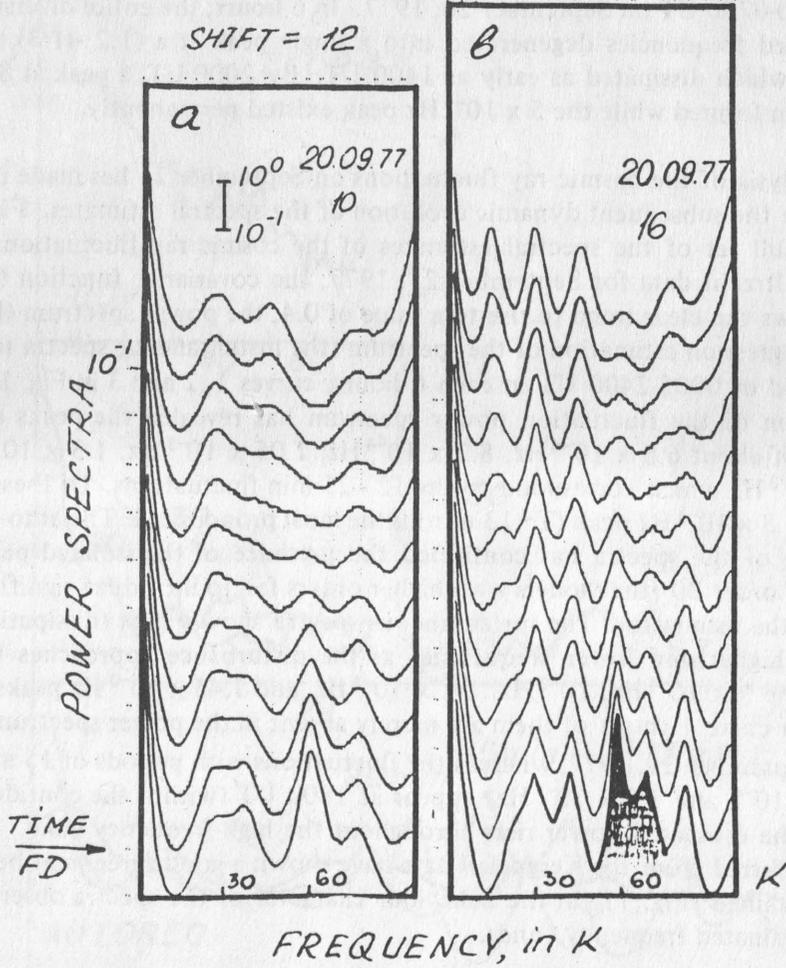


Fig. 9. The dynamic spectra of the cosmic ray fluctuation power on September 20, 1977 inferred from hourly data. Frequency is given in 1/60,000 Hz.

pressed peaks are observed in the spectra at frequencies of about 5×10^{-4} and 10^{-3} Hz by 0600-0700 UT on September 20, 1977. In 6 hours, the entire diversity of the discriminated frequencies degenerated into a single peak at a $(1.2 - 1.3) \times 10^{-3}$ Hz frequency which dissipated as early as 1400 UT. By 2000 UT, a peak at 8.3×10^{-4} Hz had been formed while the 5×10^{-4} Hz peak existed permanently.

The analysis of the cosmic ray fluctuations on September 21 has made it possible to estimate the subsequent dynamic evolution of the spectral estimates. Fig. 10 presents the full set of the spectral estimates of the cosmic ray fluctuations inferred from the Utrecht data for September 21, 1977, the covariance function (Fig. 10a) which shows the clear trend to rise to a value of 0.4, the power spectrum (Fig. 10b), the auto-regression estimation of the spectrum (the instantaneous spectra for the 24-hour period of 0005-2400 UT in each 6 hours, curves 1, 2 and 3 in Fig. 10c.). The examination of the fluctuation power spectrum has revealed the peaks at the frequencies of about 6.5×10^{-4} Hz, 8.3×10^{-4} Hz, 1.05×10^{-3} Hz, 1.3×10^{-3} Hz, and 1.45×10^{-3} Hz which correspond to the 12 - 25 min fluctuations. Of these frequencies, the 1.3×10^{-3} Hz peak ($T \sim 13$ min) is the most pronounced. The auto-regression estimation of the spectra has confirmed the presence of the isolated peaks in the models of order 20 (the models with higher orders fail to introduce significant alterations to the estimates). The instantaneous spectra show a shift (dissipation) of the peaks to higher and lower frequencies as the disturbance approaches the Earth, namely, the 9×10^{-4} Hz, 10^{-3} Hz, 1.1×10^{-3} Hz, and 1.45×10^{-3} Hz peaks are clearly seen on curve 1 (most of them are merely absent in the power spectrum) at 0600 UT on September 21, 1977, whereas the fluctuations with periods of 15 and 20 min ($f \sim 8.3 \times 10^{-4}$ and 1.3×10^{-3} Hz) appear at 1800 UT (within the confidence interval) and the estimated power rises throughout the high-frequency band. Similar estimates inferred from the Kerguelen data have shown a good agreement between the results obtained (Fig. 11) in the behaviour character of the spectra observed and in the discriminated frequency bands.

The study of the fluctuations in the intervals with Forbush decreases (the decay phase on September 22, 1977) has shown that the covariance function falls gradually (Fig. 12a). The peaks of the cosmic ray fluctuation power spectrum (Fig. 12b) inferred from the Utrecht data do not exceed the 95% confidence level (with the window width of about 15) and exhibit a large spread of their amplitudes ($\sim 99\%$) as the window width increases up to 90 at all the studied frequencies. The dynamics of the formation and rearrangement of the spectra (Kerguelen data) can be properly

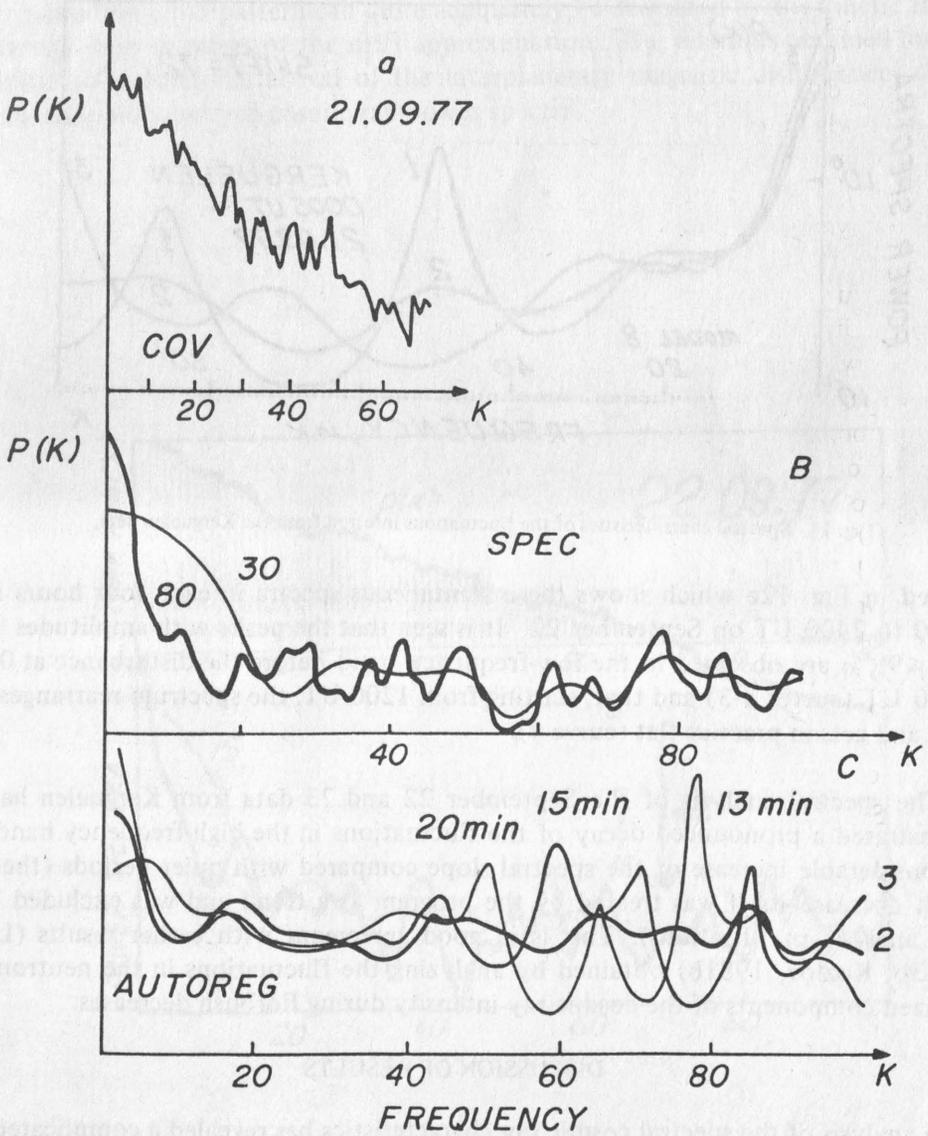


Fig. 10. The spectral estimates for the September 21, 1977 interval. (a) Covariance function; (b) Power spectrum; and (c) Auto-regression estimation. Frequency in $1/60,000$ Hz.

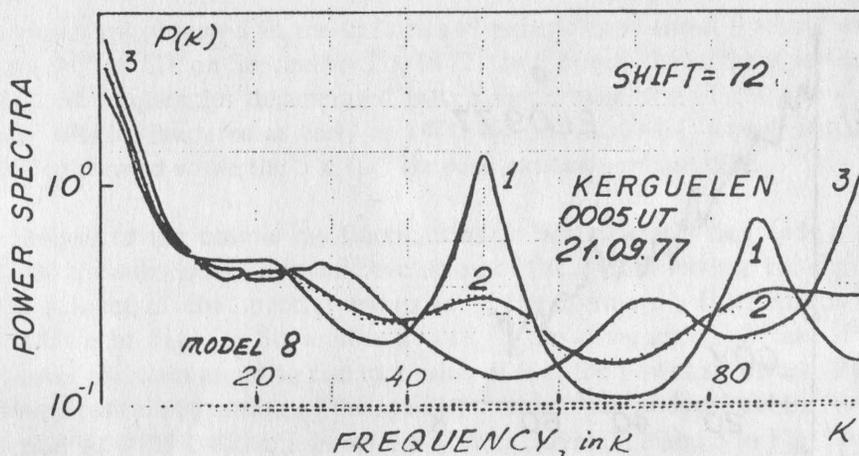


Fig. 11. Spectral characteristics of the fluctuations inferred from the Kerguelen data.

traced in Fig. 12c which shows the instantaneous spectra in each four hours from 0400 to 2400 UT on September 22. It is seen that the peaks with amplitudes $95\% \leq A \leq 99\%$ are observed in the low-frequency band before the disturbance at 0005-1200 UT (curves 1-3) and that, starting from 1200 UT, the spectrum rearranges rapidly and gets in practice flat (curve 4).

The spectral analysis of the September 22 and 23 data from Kerguelen has demonstrated a pronounced decay of the fluctuations in the high-frequency band and a considerable increase of the spectral slope compared with quiet periods (the Forbush decrease itself was treated by the program as a trend and was excluded from the analysis of filtrations). This is in good agreement with earlier results (Libin, 1983b; Kozlov, 1981b) obtained by analyzing the fluctuations in the neutron and ionized components of the cosmic ray intensity during Forbush decreases.

DISCUSSION OF RESULTS

The analysis of the spectral cosmic ray characteristics has revealed a complicated and varying pattern of the occurrence and disappearance of the quasiperiodic fluctuations in the intensity of the proton, muon and electron fluxes on the Earth surface and at various altitudes in the atmosphere and in the interplanetary space. As a first

approximation, the pattern can quite adequately be described by the kinetic theory of cosmic rays in terms of the drift approximation. The relations obtained make it possible to predict the arrival of the interplanetary magnetic disturbances at the Earth using the observed cosmic ray power spectra.

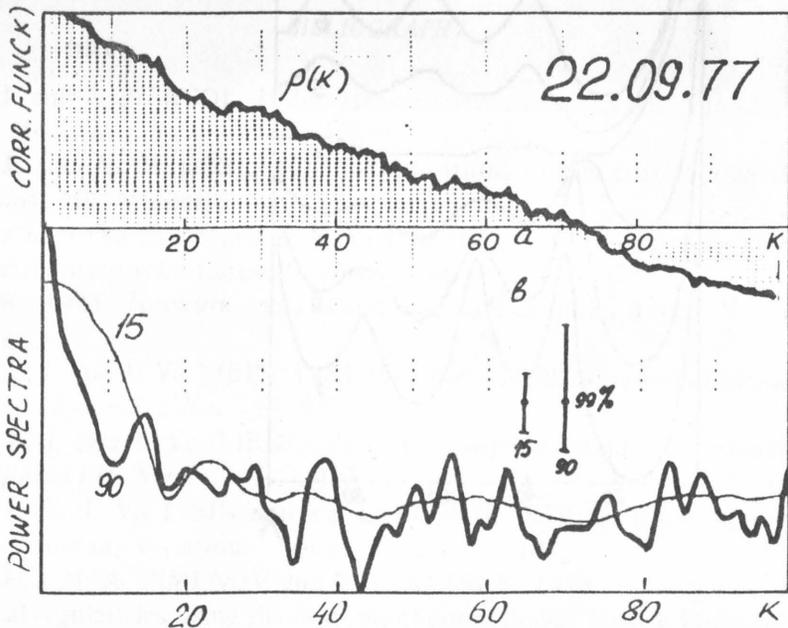
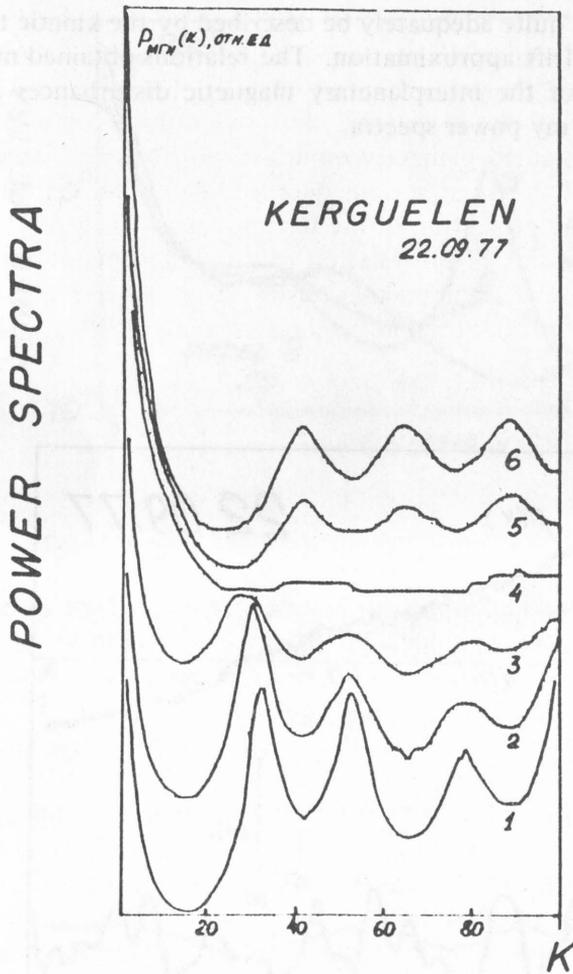


Fig. 12. Spectral characteristics during the Forbush decrease decay phase inferred from the Utrecht data. (a) Covariance function of the cosmic ray intensity on September 22, 1977. (b) Power spectra. (c) The instantaneous fluctuation spectra on September 22, 1977 inferred from the Kerguelen data. Frequency in $1/60,000$ Hz.



12(c)

We consider the prospects of future studies of cosmic ray fluctuations, and their application to continuous diagnosis and predictions, to be contingent upon the further development of theoretical approaches (the kinetic theory of fluctuations, the approximations in terms of the isotropic and anisotropic diffusion, the fluctuation

theory for the process of cosmic ray generation and subsequent propagation in the corona, the interplanetary space, and the Earth magnetosphere), upon the extension of experiments (detection of cosmic ray fluctuations with ground-based high-precision instruments in various asymptotic directions, the use of the worldwide network of neutron monitors as a unified planetary omnidirectional superinstrument, the detection of cosmic ray fluctuations at various depths underground, on balloons and on spacecrafts), and upon the perfection of the techniques for analyzing experimental data (the real-time processing of information by the independent methods controlling each other). Such advances will make it possible to solve quite a number of important problems bearing on quantitative diagnostics and prediction of such events as powerful solar flares, interplanetary shock waves, and disturbances propagating in interplanetary medium.

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