Short-period variations in cosmic-ray intensity

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Usp. Fiz. Nauk **145**, 403–440 (March 1985)

The origin and propagation mechanisms of fluctuations in the cosmic rays observed by instruments on the ground, in the stratosphere, and in space are discussed. Recent experimental results on fluctuations at frequencies from 10^{-3} to 10^{-6} Hz are discussed. The primary cause of the statistically significant fluctuations in the cosmic rays is the scattering of charged particles of the cosmic rays by random inhomogeneities of the interplanetary magnetic field.

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1. INTRODUCTION

Because of the high temperature and the low temperature gradient along height, the solar corona is not at hydrostatic equilibrium. It is continuously expanding into interplanetary space. The resulting outflow of coronal plasma is known as the solar wind. The presence of a magnetic field gives rise to various types of structures in the solar wind (inhomogeneities, discontinuities, and loops). Quite close to the sun, the pressure and inertial forces of the solar wind become much stronger than the forces of the magnetic field of the corona, and they carry this field into interplanetary space, thereby giving rise to the interplanetary magnetic field. At a distance of the order of $20r_{\odot}$ from the sun, the expansion of the corona becomes radial, and the field configuration is determined by the rotation of the sun, which twists the magnetic lines of force into Archimedes spirals which lie on cones traced out by the rotation of the radius vector.

Modern models of the solar wind and of the interplanetary magnetic field are reviewed in Refs. 1 and 2. The field is assumed to be frozen in the plasma of the solar wind ("frozen in" means that the scale time required for the diffusion of a magnetic line of force over some distance is much longer than the time required for the transport of a line of force over the same distance in the direction in which the solar wind is moving). The field is assumed to be spiral or nearly so and to be rotating with a period on the order of the solar rotation period (27 days).

The solar wind and the magnetic fields frozen in it pass by the earth at a velocity on the order of 300–700 km/s and largely determine the "weather" in the space environment of our planet: It is the variations of the solar wind, which is interacting with the magnetic field of the earth, which are the primary causes of such events as geomagnetic storms and all their manifestations. Systematic observations of the solar wind are accordingly necessary for research in geophysics and astrophysics. In particular, a study of the turbulence in the solar wind is one of the central problems of modern astrophysics. The propagation of shock waves in a turbulent medium in space gives rise to many physical processes, in particular, the scattering and acceleration of the charged particles of the cosmic rays.

Sensitive probes of the solar wind are the cosmic rays, which can furnish information on not only the large-scale processes in the solar wind but also the small-scale structure of the wind in a study of short-period changes (variations) in the cosmic-ray intensity at the earth's surface, underground, in the atmosphere, in the stratosphere, and directly in space. The hierarchy of cosmic-ray variations is quite complicated,[1] ranging from secular and 11-yr variations down to irregular variations with periods of a few minutes. As a rule, the sources of the variations of the different types can be clearly identified (this is true at least of the long period variations). As for the short-period variations in the cosmic-ray intensity, we note that it is exceedingly complicated both to observe these variations and to identify their sources. On the other

0038-5670/85/030233-24$01.80

hand, compensation is made for all this difficulty by the surprising possibilities presented by these slight and irregular changes in cosmic-ray intensity. In the modern scientific literature, the term "short-period variations" in cosmic-ray intensity is replaced by "fluctuations" or "scintillations" of cosmic rays, which mean rapid changes (with periods ranging from a few minutes to a few hours) in the cosmic-ray itensity detected with respect to the average background intensity. The background intensity level is of course chosen in different ways for short-period variations of different durations.

Short-period changes in cosmic-ray intensity were first observed by Dhanju and Sarabhai in the late 1960s. Although today the study of these variations is a well-established field in space physics, the main question—the nature of the observed cosmic-ray fluctuations—remains unresolved in many studies. The problem is that it is a complicated and laborious process to distinguish and study these short-period changes in the cosmic-ray intensity. The only methods which were available until recently for studying the spatial and temporal variations in the flux density, spectrum, and composition of the cosmic rays ran into serious difficulties in attempts to study short-period changes (fluctuations), since in order to distinguish the fluctuations and to determine their nature it was necessary (on the one hand) to deal with time-varying processes with continuously varying amplitudes, phases, and frequencies and (on the other hand) to distinguish and study the many correlations between the fluctuations themselves and various geophysical, heliophysical, and astrophysical processes. The usual correlation methods which proved insufficiently informative because of the small data files which are used (if large data files are used, the results are smeared over, and the information which might be extracted is masked; this circumstance was of particular importance in the results of the early studies). For this reason, the comparatively recent approach of using spectral methods (which are quite familiar in radio physics) to distinguish fluctuations has been a turning point in this field of space physics. Spectral methods have made it possible not only to detect oscillations with various periods in data on the cosmic rays (and to evaluate the reliability of these oscillations) but also to carry out qualitative and quantitative comparisons of various processes. Study of the dynamics of cosmic-ray fluctuations and analysis of their appearance and development, in association with various geophysical and heliophysical phenomena and their parameters, has made it possible to extract several curious results: Sharp increases in the amplitudes of the oscillations stem from flare activity on the sun, the structure of the solar wind, and perturbations of various types near the earth. It is here that we can see the enormous possibilities for space physics which are hidden in data on the short-period changes in the cosmic rays—possibilities which even today allow us to use cosmic-ray fluctuations as a forewarning of space perturbations.

As cosmic rays propagate through interplanetary space, several fluctuational phenomena occur in connection with the scattering of charged particles by random inhomogeneities of the interplanetary magnetic field.[1-3] From the published data it is possible to draw several quite general conclusions about the nature and sources of the cosmic-ray fluctuations[4]:

1) fluctuations in acceleration processes;
2) fluctuations during propagation in the solar corona and in the escape from the solar quasiconfinement[1];
3) fluctuation processes during propagation in interplanetary space and in the local galaxy;
4) fluctuations during passage through the earth's magnetosphere;
5) fluctuations due to short-period variations in meteorological factors.[4,5]

Only in observations of the various secondary components of the cosmic rays at the earth do all five of these sources operate. In observations on low-orbit satellites, geophysical rockets, and balloons, the fifth of these sources can be completely ignored. In observations outside the earth's magnetosphere, only the first three sources of fluctuations are important. It should be noted that the fluctuational phenomena caused by sources[3-5] in the galactic and solar cosmic rays are identical, so that separate information on the fluctuations of each type is important for drawing detailed conclusions from observational results.

For a thorough analysis of the factors and processes[5-40] which give rise to statistically significant fluctuations or, more precisely, to the formation and development of statistically significant fluctuations, it is necessary to identify as many as possible of the existing periodicities in the cosmic-ray itensity, working from all the information available on the various components; to follow the time evolution of these periodicities; to discard all unimportant effects; and, finally, to determine the relationships among the important processes and phenomena (and to do this analytically, to the extent possible). Governing factors here are not only the quality of the raw data but also the choice of analysis methods and the testing of the reliability of the results on the basis of some physical model or other.

2. OBSERVATION OF PERIODICITIES IN THE COSMIC RAYS (RESEARCH METHOD)

Previous methods for studying the spatial and temporal variations of the intensity, spectrum, and composition of the cosmic rays ran into serious difficulties in attempts to study fluctuational phenomena in the cosmic rays,[41-43] since in order to distinguish these fluctuations and to determine their nature it was necessary, on the one hand, to deal with time-varying processes with continuously varying amplitudes, phases, and frequencies and, on the other, to distinguish and study the numerous correlations among the fluctuations themselves and various geophysical, heliophysical, and space-physical processes.[1] The standard correlation methods and the method of statistical periodogram analysis proved insufficiently informative because of the restricted size of the data files which could be used. Studies of fluctuations on the basis of large data files resulted in a significant smoothing of the results, as is particularly obvious in several studies. For all the usefulness and versatility of the Fourier method, the corresponding calculations yield the amplitudes, periods, and phases of only nonrandom functions of the time, and thus are pertinent only when these amplitudes,

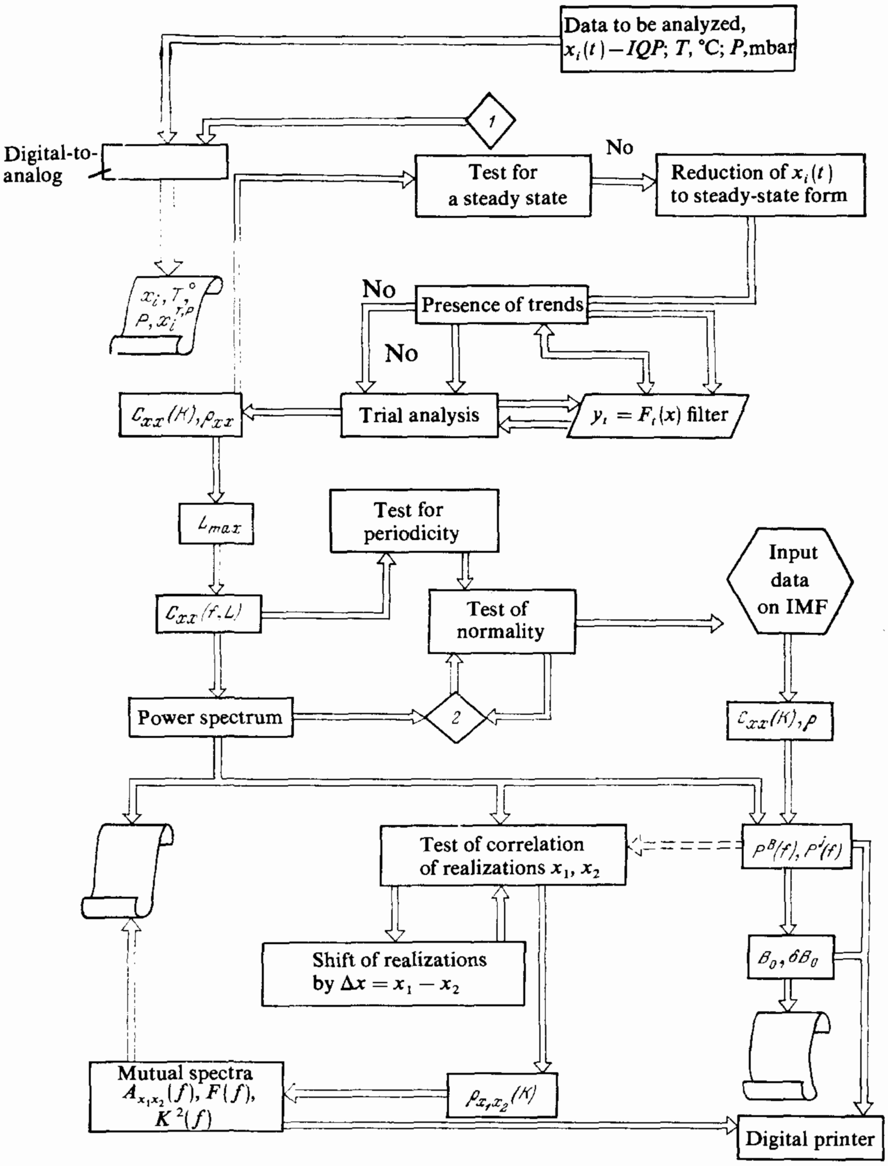

FIG. 1. Block diagram of the program for analyzing short-period variations (fluctuations) in the cosmic rays (the data to be analyzed enter the program at box 1).

phases, and periods are fixed. As Bath[44] has shown, the advantages of spectral analysis lie in the reliable and unambiguous monitoring of a comparison of different records, since the functions which are being compared are functions of the same parameter: the frequency. Essentially no serious restrictions are imposed on the behavior of the random process, and the spectral approach presents the extremely important opportunity of not only detecting prominent periods in the data but also testing their reliability, although it must be kept in mind that no mathematical model of any sort is capable of reflecting all the complexities of fluctuational phenomena in the cosmic rays.[45]

Steady-state and time-varying random processes are now the subject of a fairly extensive theoretical literature. There is accordingly no need to go into detail here on the various approaches in spectral analysis. We will simply mention the basic ideas, the basic steps of the analysis, the algorithms for finding spectra, and certain aspects of their use which are pertinent to the study of fluctuational phenomena in the cosmic rays. In practice, the procedure for evaluating spectra consists of several steps[46]: a preliminary analysis, the calculation of sampling correlation functions and spectral estimates, and the interpretation of the results.

Figure 1 is a block diagram of the analysis of fluctuational phenomena in the cosmic rays, of the correlations among these fluctuations (on the basis of observational data acquired by various instruments) at various stations, and of the various characteristics of the interplanetary medium. The labels in this block diagram are given in the terminology of Bendat and Piersol.[47] (This block diagram of the calculations is not a standard for applications; in each particular problem one would use only those steps of the analysis whose information content would lead to the desired estimates.)

a) The data to be analyzed. The data consist of the data files from measurements of the cosmic-ray intensity by neutron monitors and telescopes at various stations (or at a single station), $N_{ik}(t)$; the results of measurements of the pressure, $P_{ik}(t)$, and the temperature $T_{ik}(t)$; and the values of the coupling coefficients $W_{ik}(R)$, where i specifies the particular instrument, and k the station.

b) Corrections for meteorological conditions. The operations of correcting for the pressure and the temperature consist of a standard procedure[1–3,26] for correcting for the pressure with the barometric coefficient

$$\beta_{\text{det}}(h_0)=\frac{\int\limits_0^{\pi/2} N(h_0,\ \theta)\,\beta(h,\ \Delta\varepsilon,\ \theta)\,d\theta}{\int\limits_0^{\pi/2} N(h_0,\ \theta)\,d\theta},$$

where $\beta(h_0, \Delta\varepsilon, \theta)$ is the barometric coefficient for the particular component being used for various particle arrival angles, and $N(h_0, \theta)$ is the effective directional pattern of the instrument; and for correcting for the temperature

$$W_{\text{T, det}}(h_0,\ \Delta\varepsilon)=\frac{\int\limits_0^{\pi/2} W_{\text{T}}(h_0,\ \Delta\varepsilon,\ \theta)\,N(h_0,\ \theta)\,d\theta}{\int\limits_0^{\pi/2} N(h_0,\ \theta)\,d\theta}.$$

Values of the densities of the temperature and barometric coefficients for various particle arrival angles and various observation levels are given in Ref. 33.

c) Choice of optimum analysis interval. The idea here is to introduce an interval of frequencies to be studied, $f_1 \leq f \leq f_2$, where $f_1 \geq 10^{-5}$ and $f_2 \leq 10^{-2}$ Hz for the cosmic-ray fluctuations caused by scattering by random inhomogeneities of the interplanetary magnetic field, and $f_1 \geq 10^{-7}$ and $f_2 \leq 10^{-5}$ Hz for fluctuations caused by the sector structure of the interplanetary magnetic field. The data digitization interval is determined:

1 min for $10^{-3} \leq f \leq 10^{-2}$ Hz,
5 min for $10^{-4} \leq f \leq 10^{-3}$ Hz,
1 h for $10^{-5} \leq f \leq 10^{-4}$ Hz,
12 h for $10^{-6} \leq f \leq 10^{-5}$ Hz,
24 h for $10^{-7} f \leq 10^{-6}$ Hz.

d) Test for a steady state. The record is broken up into n equal intervals; mean values of the data and the dispersion are calculated for each interval; and these sequences are checked for the presence of trends or other time variations which cannot be attributed exclusively to the sampling variability of the estimates. *The convergence of autocorrelation functions of the intervals is tested. The program is stopped, and the intermediate information is displayed as plots of the raw data files and of the autocovariational functions.*

e) Reduction of the processes to a steady-state (or quasi-steady-state) form. This step means eliminating trends, filtering the data, etc.[44–46] There is a return to the "Test for a steady state," and the program is stopped for a second time.

f) Trial analysis. This step involves a preliminary evaluation of sampling power spectra, deciding on the need of some particular filter, and deciding whether to study the spectrum over the entire frequency range or only a part of it. The program is stopped for a third time.

g) Spectral analysis. Autocovariational and autocorrelation functions and sampling power spectra are determined. The appropriate cutoff point is chosen (the spectral window is narrowed), and the results in one-dimensional data files are reported. The program is stopped for a fourth time. Results are sent to an alphanumeric printer and a plotter.

h) Test for periodicity. Theoretically, the presence of quasiperiodic components in a random process will be manifested as δ-functions in its spectral density.[47] In practice, the spectral density is found to contain sharp peaks, which may be erroneously attributed to a narrow-band random noise, so that the analysis of periodicity is carried out on the basis of calculations of autocorrelation functions and sampling power spectra, the results of the trial analysis, and the physical interpretation of these results. Information on the frequencies identified and on the amplitudes at these frequencies is extracted as the product of a visual control. The test for periodicity is actually the initial stage of preparation for two-dimensional analysis.

i) Determination of the probability distribution.[1)] According to Ref. 47, the probability distribution of a random, quasisteady process x_n $(n = 0, 1, 2, \ldots, N)$ with a zero mean deviation $\bar{x}$ can be estimated from

$$\hat{P}(x)=\frac{N_x}{NB},$$

where B is a narrow interval positioned symmetrically with respect to x, and N_x is the number of values of the realization which fall in the interval $x \pm B$. The value of $\hat{P}(x)$ is found by partitioning the entire file of values of x_n to be analyzed into the appropriate number of subfiles of equal size, tabulating the values of x by subfile, and dividing by the width of the subfile, B, and the sample size N in such a manner that N values of the sequence $\{x\}$ will satisfy the condition $N = \sum_i N_i$. The determination of the probability distribution is a completely optional step; it is used as an auxiliary step for testing the resulting distributions for normality.

j) Test of normality. The probability distribution found for the values of the process under study is compared with a theoretical normal distribution. One of the most convenient tests of normality is the χ^2 test, in which the distribution

$$\chi^2=\sum_{i=1}^{k}\frac{(f_i-F_i)^2}{F_i}$$

is used as a measure of the discrepancy between the theoretical and observed distributions; here k is the number of intervals into which the data are grouped, and f_i is the number of observed values in interval i (Ref. 47). The test for normality, like the preceding test, is used extremely rarely—only in solving special problems.

k) Test of correlation of realizations. The question of whether there is a correlation between the files of input data is resolved. In many cases it is sufficient to visually estimate the basic physical properties of the original processes. In general, the test involves calculating mutual correlation functions, a mutual correlation coefficient, and coherence functions. The shift between realizations is estimated in this step.

l) Test of equivalence of uncorrelated realizations. This test combines the results of the analysis of the individual realizations for which statistical equivalence has been established. This operation is performed by calculating the corresponding mean weighted values from the estimates found in the analysis of the individual realizations: While estimates of the spectral density $\mathscr{G}_1(f)$ and $\mathscr{G}_2(f)$ with the corresponding degrees of freedom ν_1 and ν_2 (the condition $\nu_1 = \nu_2$ is generally assumed) are found from the individual realizations, the resultant estimate of spectral density is found in the form

$$\mathscr{G}_r(f) = \frac{\mathscr{G}_1(f)\,\nu_1 + \mathscr{G}_2(f)\,\nu_2}{\nu_1 + \nu_2};$$

the number of degrees of freedom of this estimate is[56] $\nu_r = \nu_1 + \nu_2$.

m) Determination of mutual correlation functions and mutual spectra. This step, carried out in accordance with the algorithms of Refs. 46 and 47, involves knowledge of the relationships which can be observed between different realizations of a process under study or between different processes.

n) Determination of coherence functions. This step is required for estimating the correlation of the realizations, for estimating the accuracy of the estimates of the frequency characteristics, and, finally, for directly solving several applied problems for the program (shifting processes with respect to each other, determining the statistical delay between processes, etc.). The determination of coherence functions precedes the determination of the mutual power spectra of the amplitude and phase functions. The determination of the frequency characteristics is carried out only when information on the spectrum as a whole is not required, and all that we need are the amplitudes and phases at the prominent frequencies, i.e., where the coherence function is at a maximum.

The block diagram shown here may be thought of as one way to extract information about cosmic-ray fluctuations. In many respects, the choice of units depends on the particular problem, the capabilities of the computers to be used, and the accuracy required. The block diagram shown here has been implemented as three programs. We wish to stress that each of the units is implemented as a subprogram, so that the three programs largely intersect.

In concluding this section we stress that we are making no claim that this review of existing methods for analyzing fluctuational phenomena in the cosmic rays (with several recommendations) gives a complete description of all the methods in use. Good results have been obtained by N. P. chirkov *et al.* by means of the SVAN program library and by V.I. Kozlov by a continued-fraction method. Nevertheless, the approaches described here make it possible to carry out detailed studies of specific fluctuational phenomena at prominent frequencies (or over a broad frequency range) and to estimate their relationships with various processes in interplanetary space.

To pursue the study of processes in interplanetary space on the basis of data on the cosmic rays we need a complete picture of how these processes influence the appearance and evolution of the fluctuations, and we need to calculate the relationships between the observed fluctuations with the corresponding fluctuations in the interplanetary magnetic field.

3. EXPERIMENTAL STUDY OF COSMIC-RAY FLUCTUATIONS BY MEANS OF GROUND-BASED OBSERVATIONS OF VARIOUS SECONDARY COSMIC-RAY COMPONENTS

The development of several highly accurate instruments for studying cosmic rays over the last decade has made it possible to acquire reliable data on the fluctuations of galactic cosmic rays (and, during periods of intense proton flares, of solar cosmic rays). It should be noted that regular, standardized observations have been carried out and continue to be carried out at a worldwide network of stations, generally with an hourly digitization. In order to bring out the effects of interest more reliably, the observational data must be averaged over several stations or over several instruments (since the accuracy of any single instrument is inadequate in comparison with the amplitudes of the effects). The use of instruments with an accuracy no worse than 0.2–0.3% per minute makes it possible to analyze in detail the various fluctuational phenomena in the cosmic rays on the basis of each separate instrument.[5,33]

a) Instruments for detecting cosmic rays. The requirements of a high statistical accuracy, stability, and operating reliability of all parts of the apparatus and instruments for detecting cosmic rays over prolonged periods of time leave their stamp on the design of the instruments. The development of highly accurate apparatus by simply increasing the areas of the measuring instruments is not sufficient: it is necessary to reach a reasonable compromise between the number of detectors in the apparatus and reliability, so that the number of failures and the existing instability of each part of the instrument will not render the existing apparatus uncontrollable.

A governing role is presently being played in research on the nature of the cosmic-ray variations, particularly the short-period variations (fluctuations), by the complex method of detecting cosmic rays simultaneously by various instruments at many points on the globe, at various latitudes and longitudes, at various heights and underground. Various types of variations are being studied: variations of the global and directed intensities of the meson component; variations in the neutron intensity at sea level; variations in the fluxes of protons, electrons, and various nuclei of the primary cosmic rays in the stratosphere and outside the atmosphere; etc.

The most successful of all the instruments which have been used to date in space physics is the NM-64 neutron supermonitor, which is used at all the cosmic-ray stations around the globe. This neutron monitor consists of three six-counter sections, each having dimensions on the order of $315\times220\times50$ cm and weighing about 12 metric tons. At high latitudes, the count rate is usually about 240 000 to 250 000 counts per 1 h of measurements, while at low latitudes the typical count rate is 200 000 to 220 000 counts per 1 h. The detector in this neutron monitor consists of two-meter proportional counters 15 cm in diameter filled with gaseous BF_3 enriched in the isotope B^{10}. The counters are cased in lead, which is used as a neutron generator (the effective area is of the order of 6.2 m^2), and polyethylene, which is used as a neutron moderator and reflector. The neutrons are detected in the proportional counter by virtue of the reaction

$$B_5^{10} + n_1^0 \rightarrow Li_3^7 + He_2^4,$$

since the neutrons are easily captured by boron nuclei. This reaction liberates an energy of the order of 2.5 MeV, about 1.6 MeV being carried off by the α particle, and 0.9 MeV by the lithium nucleus. The two particles are emitted in opposite directions, forming 80 000 ion pairs. The appearance of α particles and a large number of ions in a counter results in a discharge in the counter and a relatively large pulse at the output of the system, which marks the fact that a neutron has struck the counter. (Since BF$_3$ is a quenching gas, the counter can operate stably at a gain of the order of several thousands.) An important characteristic of a neutron monitor is the number of neutrons which are produced by protons and π mesons of various energies. [The cosmic-ray neutrons are of secondary origin; i.e., they are formed as a result of the interaction of the nuclear-active component of the cosmic rays (the primary particles, mostly protons, and also a variety of secondary particles—mesons formed in the atmosphere) with the nuclei of atoms of the air.] Since the particles involved in the production of the neutrons are primarily stable particles, the neutron intensity is determined only by the mass of matter above the apparatus. The air temperature has essentially no effect on the formation of neutrons; there is only a barometric effect, which is easily taken into account. Studies carried out by various investigators (reviewed in Ref. 1) have shown that the fraction of neutrons which are produced in a monitor as a result of neutrons produced in the atmosphere is of the order of 80%, and the fraction of neutrons which appear as a result of the incidence of protons on the monitor is only 10–12%.

The detection of cosmic rays by means of neutron monitors does have some disadvantages. The neutron monitor is an instrument which gathers cosmic rays from all directions. Several problems require detection of the cosmic-ray intensity from a certain direction. Such measurements can be carried out only by means of cosmic-ray telescopes, of the scintillation or counter type.

Furthermore, cosmic-ray telescopes can be used not only to study the intensity of cosmic rays coming from various directions but also to carry out these measurements underground. This versatility is particularly important in the detection of cosmic rays of extremely high energy.

There are some common features in the wide variety of telescopes: Groups of detectors are connected in coincidence circuits, so that it is possible to select exclusively those events in which cosmic-ray particles pass through all the groups of detectors connnected in the coincidence circuit. Lead shields of various thicknesses, which absorb low-energy particles, are placed between the different detectors to separate the particles by energy. Figure 2 sketches the structure of the scintillation telescope of the Institute of Terrestrial Magnetism, the Ionosphere, and Radio Wave Propagation[5,34] (parts 1–4 and 7 constitute a supertelescope, 6 is a neutron monitor, and 5 are conditioners). The scintillation telescope consists of four identical instruments, each having an area of 4 m^2, which detect cosmic-ray particles from the north, the south, the west, and the east and at intermediate azimuthal directions at zenith angles of 27°, 45°, and 60° and at a vertical particle-arrival direction. The detectors of the scintillation telescope form a truncated pyramid at whose lower base there is a plastic scintillator with an area of 1 m^2. At its upper base there is a photomultiplier which detects the photons produced as the cosmic rays pass through the material of the scintillator. The use of a set of four instruments instead of a solid "carpet" (Fig. 3a) makes it possible to use any of these instruments in any experiment as desired, without any significant loss of continuous detection; to replace and service any of the instruments; and to eliminate information resulting from natural radioactivity, especially in underground experiments.

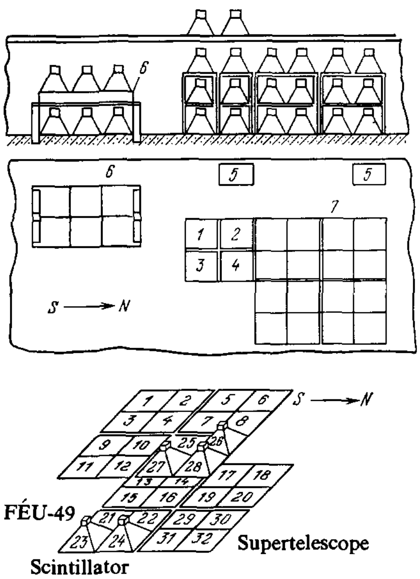

FIG. 2. Construction of the scintillation telescope of the Institute of Terrestrial Magnetism, the Ionosphere, and Radio Wave Propagation (IZMIRAN).

The use of scintillation detectors in cosmic-ray physics marks the completion of a genuine revolution in this field: In addition to a more detailed study of known types of variations, it has become possible to close in on the study of variations with short and very short periods. The possibility of using huge areas, the excellent temporal stability of the characteristics of the scintillators, the short flash time, and other characteristics make scintillators exceptionally promising for studying cosmic-ray fluctuations in ground-based and underground settings. (Figure 3 shows a scintillation telescope and a neutron monitor used for detecting cosmic rays.)

b) Fluctuational phenomena in the cosmic rays according to data obtained with various instruments. The first detailed observations of cosmic-ray intensity, carried out by Dhanju and Sarabhai[52,53] by means of a cosmic-ray scintillation apparatus with an area of 60 m^2 at Chacaltaya, Bolivia, resulted in the discovery of short-period variations in the intensity which turned out to be quite regular over a pro-

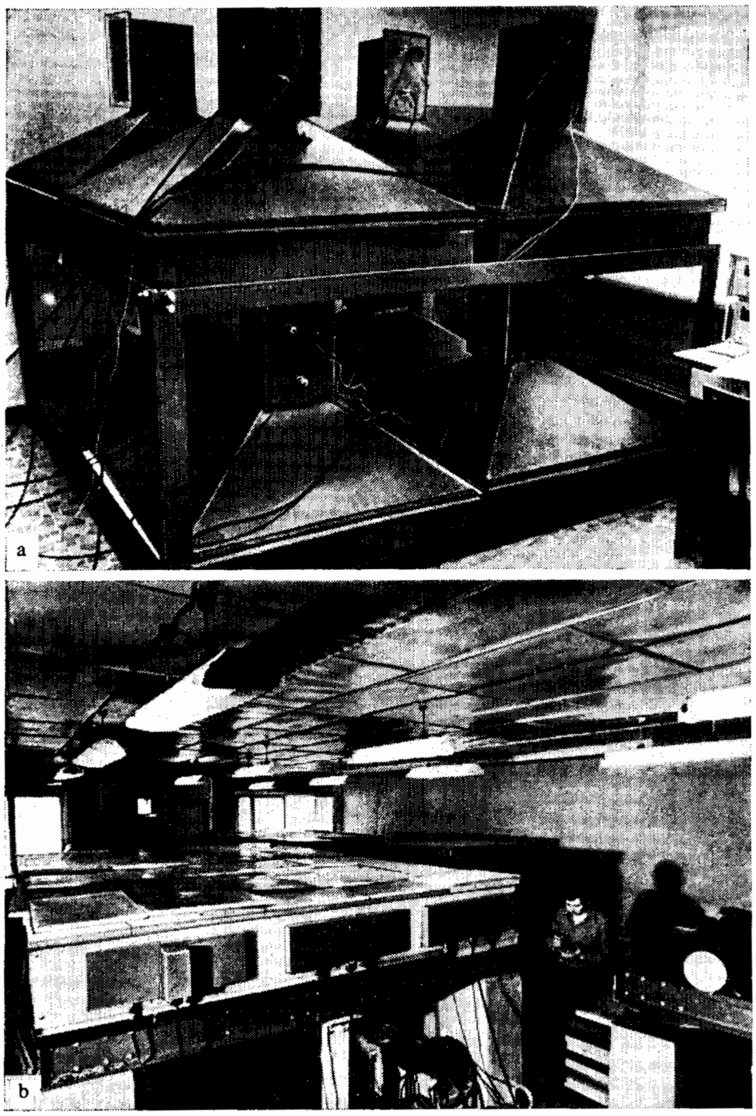

FIG. 3. a—The scintillation telescope for the underground observatory at Ala-Archa in the Kirghiz SSR; b—neutron supermonitor of the Institute of Terrestrial Magnetism, the Ionosphere, and Radio Wave Propagation (IZMIRAN).

longed time. Dhanju and Sarabhai's apparatus, with an average count rate of the order of 10^6 counts/min, consisted of three identical instruments which were installed at a height of about 17 200 feet. The data on the cosmic rays were recorded every 12 s, and the pressure was measured each minute. The power spectrum of the fluctuations was analyzed on the basis of data files each containing 180 values, with an overall delay of the order of 30 and with a digitization interval of about 1 min. Spectral estimates found from considerable observational material (Fig. 4) show that the peaks in the power spectra of the fluctuations are permanent features in all the 3-h intervals studied by the investigators. When the spectral estimates are combined, it is found that the peaks are smeared only slightly in the interval of spectral frequencies from 1 to 6 cycles per hour, largely due to imperfections of the data analysis. Nevertheless, peaks are observed in the high-frequency region (at 15–16, 18, and 25 cycles per hour) which are essentially immune to smearing.

A major research effort on fluctuations of the cosmic-ray neutron component has been carried out for a long time now by means of the neutron supermonitors of the worldwide network of cosmic-ray stations. The hourly and 5-min data on the cosmic-ray intensity over the years 1966–1969 at the stations at Alert, Deep River, Sulphur Mt., Chacaltaya, and Calgary (the range of geomagnetic cutoff rigidities is 0.1–15 GV) have yielded cosmic-ray fluctuations over the broad frequency range[54,55] 10^{-7}–10^{-3} Hz. After the peaks due to the rotation of the earth and the sun are eliminated, the spectrum of cosmic-ray fluctuations becomes a very smooth power-law function $f^{-\gamma}$ (where $1.65 \leqslant \gamma \leqslant 1.95$) with peaks at certain basically fixed frequencies.

Our understanding of the fluctuations in the nucleon component of the cosmic rays has benefited substantially from studies by Kozlov, Krymskiĭ, and Chirkov[56–63] on the basis of cosmic-ray measurements at the earth by the neutron supermonitors at the Tixie Bay, Yakutsk, and Khabarovsk stations over the years 1969–1983. This analysis used observation intervals with a substantial range of environ-

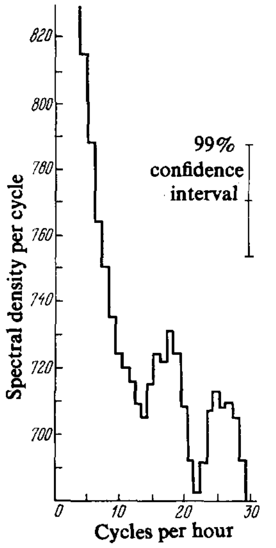

FIG. 4. Spectral characteristics of cosmic rays according to measurements at the Chacaltaya station.[52,53]

ments in interplanetary space and in the earth's magnetosphere. In addition to the disturbed intervals 15–21 May 1969, 20 July to 2 August 1972, 18–24 January 1973, and 12–18 April 1973, there were control intervals in which the geomagnetic and solar activities were low. Comparison of the results for the different intervals revealed that stable fluctuations appear in the cosmic rays in both the low-frequency range (with periods ~7 h) and the high-frequency range (with typical periods of 15–20 and 40–50 min) during intense disturbances of the interplanetary medium and in the earth's magnetosphere. The appearance and existence of these fluctuations are characteristic of only disturbed intervals. Power spectra calculated from the mutual correlation function of the observational data from the Tixie Bay and Irkutsk stations, the Tixie Bay and Alert stations, and several other stations separated in longitude show that the 7-h variation, at least, is common to all the stations during disturbances of the interplanetary medium and the geomagnetic field. It is difficult to overestimate the value of this research, since it not only involves a study of a phenomenon which previously was essentially unknown but also raises the hope that we will acquire an effective instrument for predicting processes of various types in interplanetary space. Kozlov *et al.*[62,63] are studying the relationship between the change in the power spectrum of the cosmic-ray fluctuations calculated from data acquired by the neutron supermonitors and the passage of intense shock waves. The increase in the amplitude of the fluctuations in a rather narrow spectral region (we are dealing here with fluctuations with typical periods of about 20 and 40 min) before the arrival of the shock front, followed by a significant decrease in this amplitude after the passage of the front, gives us information about the dynamics of the propagation of shock waves. The very fact that an increase occurs in a certain part of the spectrum "is a sort of forerunner of the approaching shock wave, and the absence of these fluctuations allows us to say that we have discovered a 'wake' behind the front of the propagating shock wave."[63] This effect is analyzed in detail below; here we simply wish to stress that a study of the cosmic-ray fluctuations makes it possible to identify reliably the fact that a shock wave is passing, even in the essentially total absence of explicit manifestations of the influence of this shock wave on the global cosmic-ray intensity (i.e., even in the absence of Forbush decreases). For example, the disturbances of the interplanetary medium observed on 22 September and 22 November 1978 could barely be seen in data on the cosmic-ray intensity at high-latitude stations. During September 1978 no effect at all of interplanetary perturbations on the observed cosmic-ray intensity was seen (or, at least, nothing could be seen visually). Nevertheless, the appearance of fluctuations with periods of the order of 20 and 40 min in the cosmic-ray measurements was perfectly clear.[41]

c) Cosmic-ray fluctuations during Forbush decreases in the cosmic-ray intensity at the earth; correlation between these fluctuations and those of the interplanetary magnetic field. Research on fluctuations in the intensity of the neutron component of the cosmic rays on the basis of data from the stations at Tixie Bay, Yakutsk, and Khabarovsk[63] at times of low geomagnetic activity has shown that the power distribution of the fluctuations is quite flat over the entire frequency range studied, with fluctuation amplitudes which do not go beyond even the 95% confidence interval. Fluctuations at the "noise" level are therefore[63] typical of unperturbed conditions in the solar wind (Fig. 5). Although a nonuniform power distribution of the fluctuations is observed before the onset of Forbush decreases caused by quasisteady structures, these fluctuations are at the level of the general "noise" (no greater than 95%). The fluctuation amplitudes do exceed the 95% confidence interval directly during quasi-steady disturbances, but the fluctuations are distributed uniformly over the entire frequency range.[63] During Forbush effect[41,62,63] caused by unsteady disturbances, on the other hand, we observe a "pumping" of the power toward higher frequencies in the spectrum (to fluctuations with periods of the order of a few tens of minutes or less) before the onset of the Forbush decrease, and we observe a pumping downward along the frequency scale (to fluctuations with periods of 40–50 min and more) during and after the Forbush decrease.

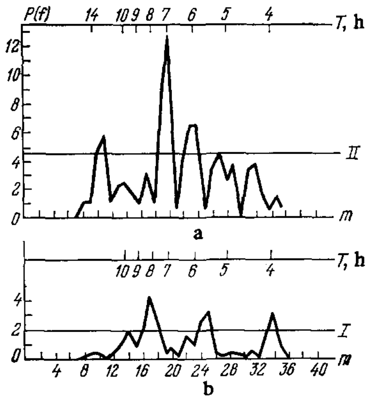

FIG. 5. Cosmic-ray fluctuations typical of (a) perturbed and (b) unperturbed conditions in the solar wind.[60–62]

Spectral estimates calculated from data from the scintillation telescope of the Institute of Terrestrial Magnetism, the Ionosphere, and Radio Wave Propagation[33] ("the Institute") over the years 1977–1979 showed that, regardless of whether there is a direct, obvious effect of interplanetary perturbations of a time-varying type on cosmic rays, there are statistically significant fluctuations (exceeding the 95% confidence interval) with periods of 17–20 and 40–60 min in the data from observations of the cosmic rays if there is a perturbation of ths type near the earth. The sensitivity of the fluctuations (i.e., the distance from the earth to the perturbation of the interplanetary medium) is determined exclusively by the dimensions of the inhomogeneities in the interplanetary magnetic field and thus the energy of the particles which are detected.[42] It should simply be noted that, particularly for the scintillation telescope of the Institute, fluctuations with periods ranging from about 20–40 to 165 min (the corresponding energies are 15–50 GeV) are detected most efficiently; this range of periods corresponds to the maximum of the coupling coefficients of the particular instrument.[5] The 5-min observations of the total ionizing component of the cosmic-ray intensity in February 1978 were used to find the frequency spectra of the fluctuations both for each day in question and for the intervals 7–12 and 7–15 February 1978. The reliability of the estimates was checked by a window contraction procedure: The spectra proved to be stable at delays of the sampling covariational function equal to 32 for 7–12, 14, and 15 February and to 64 for 13 and 7–15 February. (The interval 7–17 February was a particularly interesting part of the month because a rather strong disturbance was found at 21.45 UT on 14 February against the background of a comparatively long geomagnetically quiet interval from 1 to 12 February. Calculations of spectra showed that over the entire interval before the Forbush decrease there were no prominent frequencies in the spectra, while in the disturbed interval the power spectrum had statistically significant fluctuations lasting 12–14 and 17–20 min (Fig. 6a). A further analysis (the construction of dynamic power spectra over each day with a shift every 4 h) showed that an increase in the peaks (more precisely, an increase in their heights) in the high-frequency part of the spectrum, to a level exceeding the 99% confidence interval, occurred between 1200 and 1600, i.e., essentially several hours before the onset of the Forbush decrease. Analysis of the cosmic-ray fluctuations in April and May 1978 on the basis of the 5-min data on the cosmic-ray intensity obtained from the scintillation telescopes at the Institute and also at Bologna revealed a similar picture: The power spectra of the fluctuations over the intervals 10–13 April and from 29 April to 9 May showed fluctuations exceeding the 95% confidence interval with periods of the order of 17–20, 20–45, 95–115, and 165 min (Fig. 6b).

The spectral estimates showed that the prominent peaks were permanent features in all the individual samples of 1-day intervals. Comparison of all the spectra calculated for the interval from 28 April to 1 May (spectral estimates on the total ionizing component of the vertical and inclined telescopes of the Institute and at Bologna and on the muon component of the azimuthal telescope of the Institute were used) reveals that there is an essentially complete agreement of all the estimates: The composite spectrum suffers essentially no blurring, and there are stable peaks corresponding to fluctuations with periods of 12–13, 16, 20, 45, and 165 min. We should emphasize that several of the results from the telescope at Bologna which were used in this composite analysis were obtained with an *underground apparatus*. Nevertheless, the results agree quite well with the results of the ground-level observations. In general, a study of fluctuational phenomena in the cosmic rays on the basis of data from underground telescopes[64–68] is a topic of considerable interest. Data obtained on the hard component of the cosmic rays at Turin at a depth of the order of 70 meters water equivalent (the average geomagnetic cutoff rigidity is of the order of 8 GV, and the average particle rigidity is about 250 GV) over a 6-month interval (from September 1979 to March 1970) and over a 7-month interval (from January to July

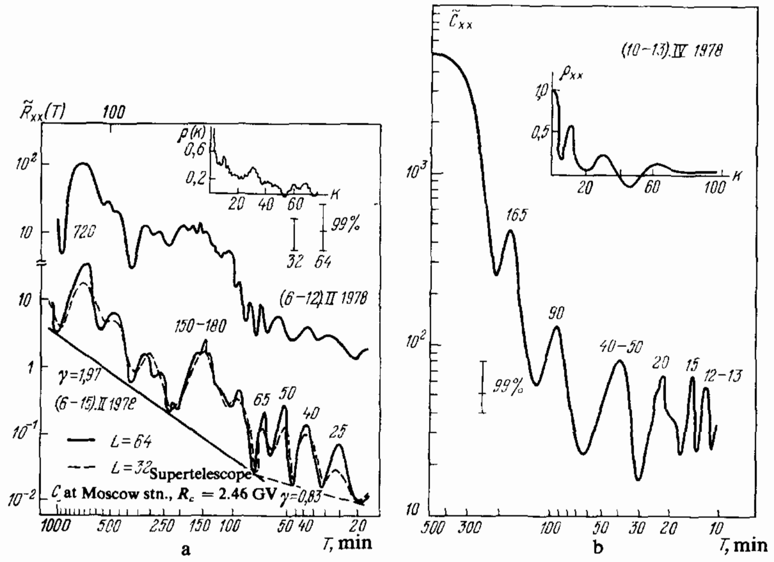

FIG. 6. Power spectra of cosmic-ray fluctuations during the intervals (a) 6–15 February and (b) 10–13 April 1978 (Ref. 41).

1971) were used to study the power spectrum of the cosmic-ray fluctuations.[68] The spectrum found experimentally for the frequency interval $5\cdot10^{-7}\leqslant f\leqslant2\cdot10^{-4}$ Hz was compared with the spectrum expected in interplanetary space (expected on the basis of the kinetic theory of cosmic-ray fluctuations with allowance for data on the power spectrum of the fluctuations of the interplanetary magnetic field, data on Forbush decreases, and data on cosmic-ray variations associated with the passage of active regions across the central meridian of the sun). These results confirmed the conclusions of the theory for a nonlinear interaction of high-energy cosmic rays with perturbations of the interplanetary magnetic field, and they confirmed the theory for a diffusive propagation of cosmic rays at rigidities up to a level of the order 250 GV, with a correction for modulation of the cosmic rays by active processes on the sun. The data from 5-min observations by a neutron supermonitor at a height of 3340 m above sea level near Alma-Ata[69b] (the geomagnetic cutoff rigidity there is of the order of 6.7 GV) were used to study cosmic-ray fluctuations in the frequency interval $3\cdot10^{-5}\leqslant f\leqslant2\cdot10^{-2}$ Hz. The frequency power spectra of the fluctuations for the quiet intervals 6–14 June 1975, 1–7 July 1977, and 20–29 September 1978 showed that the spectra are dominated by a peak corresponding to fluctuations with a period of 3 h 20 min, which strongly suppresses all other oscillations. During the disturbed interval from 30 April to 7 May 1978, oscillations in the cosmic-ray intensity with periods of the order of 15 and 23 min and also 40, 90, and 160 min were observed (Fig. 6), as in the studies by Libin.[41,42] Studies of fluctuations in the frequency interval $2\cdot10^{-7}\leqslant f\leqslant10^{-4}$ Hz on the basis of data obtained at the stations at Washington, Resolute Bay, Kiel, Deep River, and Pic du Midi showed that during disturbances the spectral index of the fluctuations varies over the interval $2.0\leqslant f\leqslant3.0$, corresponding to an increase in the number of inhomogeneities 10^{11} cm in size and larger. A study of the fluctuations of the interplanetary magnetic field during the passage of shock waves by the earth on the basis of data on cosmic-ray fluctuations completely confirmed the increase in the power in the high-frequency part of the spectrum a day before the beginning of the perturbation, followed by a pumping of power down the frequency scale. The spectrum recovers the shape typical of geomagnetically quiet conditions about a day after the beginning of the perturbation. A joint analysis of the fluctuations in the interplanetary magnetic field and in the cosmic-ray intensity reveals the simultaneous existence of oscillations with periods of 40–45 and 80–90 min, which may indicate[69–71] a turbulent generation mechanism (Fig. 7; $l=\gamma+2$).

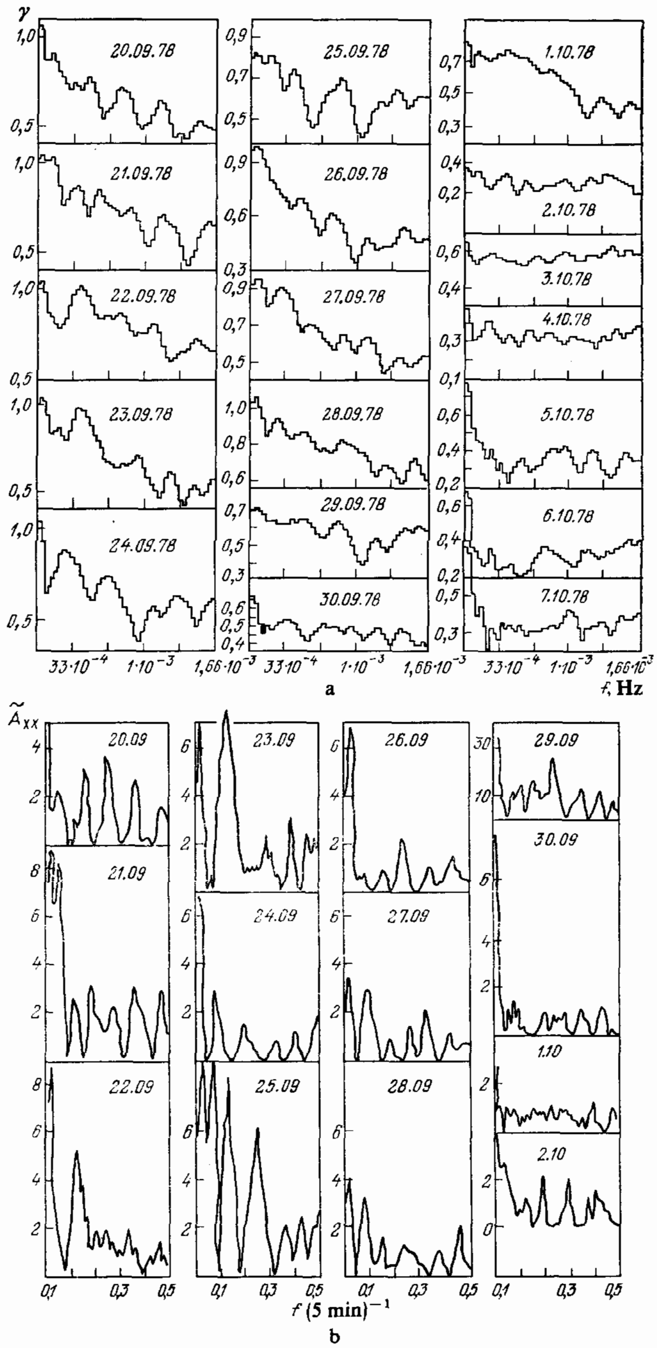

FIG. 7. Changes in (a) the index γ and (b) the power of the spectral estimates for the events in September–October 1978 (Refs. 41 and 42).

Spectral-temporal analysis has been used to study the dynamics and frequency spectra of fluctuations of the interplanetary magnetic field and of the cosmic rays at times preceding and following the onset of perturbations in the interplanetary medium near the earth for the intervals 8–10 June 1968 and 20–22 November 1977 (Ref. 69c). The results demonstrate both an essentially complete agreement of the observed fluctuations and the simultaneity of the changes in the spectra of the cosmic rays and the interplanetary magnetic field. The observed simultaneous intensification of the power spectra began 12 h before the beginning of the perturbation.

A similar change in the spectra is observed when the earth crosses a boundary in the sector structure of the interplanetary magnetic field. Analysis of measurements of the cosmic-ray intensity at the Tixie Bay station and measurements of the modulus of the interplanetary magnetic field on the satellite Explorer 33 have shown that the cosmic-ray fluctuations in the high-frequency part of the spectrum intensify a few hours before the arrival of the sector boundary; the maximum of the spectrum then moves downward along the frequency scale. This result agrees well with the model of scattering of charged particles by random inhomogeneities of the interplanetary magnetic field, since the passage of a second boundary by the earth is "perceived" by the cosmic rays as a large inhomogeneity.

d) Observations of cosmic-ray fluctuations during solar flares. Analysis of the cosmic-ray fluctuations during flares is a topic of independent interest. Transky *et al.*[70] detected some additional peaks (with relative amplitudes of the order of 15%) in the time evolution of the intensity of solar cosmic rays from the flare of 12 November 1960 by working from observations of cosmic rays by the neutron monitors at the stations at Nederhorst, London, Lindau, Leeds, Kiel, and Climax. These additional peaks appeared a few hours after the maximum was reached. Similar results were found for a flare on 4 August 1972 (with a relative amplitude of the order of 5%). Observations by the neutron monitors at Tixie Bay and Deep River revealed fluctuation frequency spectra with some typical stable peaks corresponding to cosmic-ray fluctuations with periods ranging from 30 to 150 min. At a solar-wind velocity of the order of $5\cdot10^7$ cm/s, these peaks correspond to inhomogeneities of the order of 10^{11}–10^{12} cm in size. These estimates are confirmed by those found by Libin *et al.*,[71] who worked from ground-based observations of the cosmic-ray intensity by means of the scintillation telescope of the IZMIRAN Institute on 7 May 1978 to estimate the characteristic dimensions of inhomogeneities in the interplanetary magnetic field. They found dimensions of the order of 10^{11}–$0.5\cdot10^{12}$ cm. A similar result was observed for the flare of 25 September 1978 (Ref. 72): A detailed analysis of the fluctuational phenomena in the cosmic rays shows that although the direct "inspirations" for the cosmic-ray fluctuations during flares are inhomogeneities of the random interplanetary magnetic field (particularly shock waves) the actual sources of at least some of the fluctuations simply could not be identified in the comparison with various geophysical and heliophysical parameters) are intense chromospheric flares of importance 2 and higher, which cause interplanetary and magnetospheric disturbances.[73] In fact, it is probably not isolated flares but series of flares which are responsible.[74]

4. EXPERIMENTS ON COSMIC-RAY FLUCTUATIONS AT VARIOUS HEIGHTS IN THE ATMOSPHERE, NEAR THE EARTH OUTSIDE THE ATMOSPHERE, AND IN INTERPLANETARY SPACE

The power spectrum of cosmic-ray fluctuations in the interval $3\cdot10^{-4}\leqslant f\leqslant10^{-2}$ Hz was determined by Kodama *et al.*[75] on the basis of observations on 23 May 1975 on balloons above Sanriku, Japan, with a plastic scintillator with an effective area of 4 m^2. They found a significant peak at $3\cdot10^{-3}$ Hz, which corresponds to cosmic-ray fluctuations with an amplitude of the order of 0.16% and a period of the order of 5.5 min. (Away from this peak, the spectrum is a power law $f^{-\gamma}$, where γ is 1.7 for the measurements in 1972 and 2.1 in 1975.) Fluctuations with similar periods have been observed in experiments on the electron and γ-ray fluxes in the upper atmosphere[76] with the help of high-altitude balloons. The temporal variations were anlayzed over the interval 4–60 min. Figure 8 shows the results of an averaging of five periodograms. The most reliable period is about 5 min, with an amplitude ranging up to 20% during certain segments of the flights. (Gal'per *et al.*[76] concluded that there is a genetic relationship between the 5-min fluctuations in the radiation and processes occurring on the sun.) As for fluctuations with long periods, we note that fluctuations with periods of 10–20 and 40–50 min were observed during the flights,[77–80] but these oscillations in the radiation flux were considerably less stable.

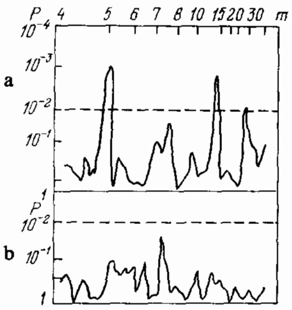

FIG. 8. Periodograms of fluctuations in the intensity of the hard γ radiation. a—In the upper atmosphere; b—at sea level.[76–78]

The γ telescope Nataliya-1 was flown on balloons on 20 August 1979 to measure γ rays with energies above 5 MeV, electrons with energies above 20 MeV, and protons with energies above 100 and 500 MeV. These measurements revealed quasiperiodic pulsations[79] in the fluxes of these particles with periods of 1.1, 1.4, 10.4, and 33 min. Similar measurements carried out on 23 August under the same conditions revealed some similar fluctuations with the same periods. The amplitudes of the observed fluctuations in the γ radiation exceeded the amplitudes of the corresponding fluctuations in the charged particles by at least an order of magnitude. This result can be explained on the basis that the γ-ray fluctuations are caused by waves and instabilities in the earth's magnetosphere. Analysis of extensive measurements of the γ radiation over the years 1972–1979 has shown[80] that these fluctuations with periods of 1, 5, 12–15, and 23–26 min are present, with amplitudes of the order of 5–20%. The flux of γ radiation is modulated most effectively with a period of the order of 5 min. We should simply point out that similar fluctuations have been observed for the same periods in data on the solar radio emission.[81,82] Kobrin *et al.*[82] studied the relationship between fluctuations in the slope of the spectrum and the intensity of the centimeter-range solar radio emission, on the one hand, and solar activity, on the other. They found that there is a relationship between the stable 20- and 40-min fluctuations in the solar radio emission, on the one hand, and proton flares, on the other[84]; the amplitudes of these fluctuations increase with increasing general activity of the sun over an interval of several days before the appearance of the flare, and they decrease quite rapidly after the flare. Some 20–24 h before a flare on the sun[85] (all the events studied stemmed from flares or series of flares of importance 2–4), there is an intense buildup of solar plasma with a period of the order of 45 min, which causes increases in the amplitudes of the fluctuations in the radio emission by a factor of 10–30 by the time of the flare. Calculations of the effect of solar pulsations on the appearance of cosmic-ray fluctuations show that the presence of 20–50-min fluctuations in the solar cosmic rays can be interpreted only on the basis of a triggering role of solar flares. It is necessary to assume only that, to a large extent, the observations of fluctuations at the surface of the earth and near the earth are related to galactic, rather than solar, cosmic rays. It should be noted that all comparisons of the spectra of cosmic-ray fluctuations and fluctuations of the interplanetary field are of a basically semiqualitative nature: No theory has been derived which gives a complete explanation of the nature and generation mechanism of the observed fluctuations in the cosmic rays. In practice, accurate estimates of the fluctuations of the interplanetary magnetic field can be found from corresponding estimates of the power of cosmic-ray fluctuations only for particles whose Larmor radius during motion in the magnetic field is significantly larger than (or smaller than) the typical dimensions of the field inhomogeneities. Nevertheless, even a qualitative (or, more precisely, semiqualitative) comparison of the results found in studies of cosmic-ray fluctuations with the corresponding fluctuations in the interplanetary magnetic field shows[27,68] that there is good agreement not only after these results are averaged over a substantial set of spectra but also after an average over specific spectra, where simultaneous measurements of cosmic rays and of the interplanetary field are available. Such cases occurred in September and November 1977, when extensive measurements of the cosmic rays and magnetic fields in interplanetary space were carried out on the earth satellites Meteor-2 (Refs. 87 and 88), SMS-2, and GOE-2 (Ref. 89) and on the space probe Prognoz,[90] at the same time as systematic observations of various components of the cosmic-ray intensity at the earth's surface.[51,86]

These comparisons agree well with results calculated on the spectra of cosmic-ray fluctuations (on the basis of data from various stations) and the spectra of the interplanetary magnetic field obtained on the IMP-3 satellite.[91] Over the frequency range from 10^{-7} to 10^{-4} Hz, the spectra can be described by $f^{-\gamma}$, with $1.5 \leqslant \gamma \leqslant 2.0$. Upon a change in the shape of the power spectrum of the fluctuations in the interplanetary magnetic field, there is an essentially identical change in the cosmic rays.[43,91] Comparison of the nature of the changes in the fluctuations over a broad frequency range (with periods ranging from 30 min to 40 h) on the basis of data from the cosmic-ray stations at Deep River, Thule, McMurdo, and Alert with measurements of the interplanetary magnetic field taken on the Mariner 4 space probe reveals not only an agreement in terms of the shape of the power spectrum of the fluctuations but also the presence of prominent frequencies in the two series of measurements.[92] Similar results were obtained in a determination of the periods of the intensity oscillations of proton and electron fluxes in the Van Allen belts on the satellite Kosmos-137 (Ref. 93). Further confirmation of the interrelationship between the fluctuations of the cosmic rays and those of the interplanetary magnetic field came from measurements on Explorers 28 and 33–35 and Helios 1 (Refs. 94 and 95): Brief changes in the proton flux density (lasting of the order of 15 min) were studied immediately before the arrival of an interplanetary shock wave which caused an SC in the geomagnetic field. This study revealed a significant growth of the fluctuations several hours before the beginning of the SC. A study of the power spectrum of the oscillations of the inhomogeneities of the interplanetary magnetic field[96] during various perturbed intervals associated with solar flares has shown that the power spectrum of the interplanetary magnetic field is dominated by periods of the order of 20–40 min. Their intensity increases sharply toward the beginning of a geomagnetic storm, and the power of the oscillations in the field components is significantly higher than that of the oscillations in the modulus of the field, although (in particular) periods of the order of 5 min, which are the periods found most frequently on the sun, were not observed.[96] We should point out that the statistical analysis of Ref. 96 was carried out by the Tukey method, which sometimes suppresses existing periodicities.[33] A mutual spectral analysis (Tukey-Parzen windows were used) of measurements of various components of the interplanetary magnetic field on the basis of data from Explorer 33 has shown[97] that there are not only a significant set of field fluctuations but also some rather easily identifiable fluctuations (exceeding a 95% confidence interval) with periods of 50 and 160 min, which correlate well with corresponding fluctuations in the cosmic rays. The maxima in the cosmic-ray intensity agree within a few minutes with the maxima in the changes in the interplanetary magnetic field. The most important result is that the maximum amplitudes of the fluctuations in the particles were observed when the space vehicle crossed tangential shocks[94,95] separating fibers of the solar wind. Both the spectra of the fluctuations in the cosmic-ray intensity and the spectra of the fluctuations in the interplanetary magnetic field had an index γ of essentially 2 at these times.[94–97] The spectra calculated from the ground-based data[98] have essentially the same indices, 1.92–2.90 for helio- and geophysically disturbed conditions and 1.1–1.5 for quiet conditions. These results also agree with direct *in situ* measurements of the interplanetary magnetic field[99,100] and the results of many theoretical studies of cosmic-ray fluctuations.[101,102] Observations over 427 days by two proton detectors[103] placed on the lunar surface by Apollo 14 have been used to study the power spectrum of cosmic-ray fluctuations over the frequency range from $2.1 \cdot 10^{-7}$ to 10^{-5} Hz. It has been found that the spectrum is a power spectrum with an index of the order of 1.1 ± 0.3, in good agreement with the results of other measurements, in particular, some ground-based measurements.[103] Since these measurements were carried out outside the atmosphere and outside the magnetosphere of the earth, this result proves that the observed fluctuations in the cosmic rays are caused, as the authors assert, by the scattering of charged particles of the cosmic rays by inhomogeneities of the interplanetary magnetic field. A comparison of the upper limit found on the power spectrum of the fluctuations of the interplanetary magnetic field[27] with that found from the observations at the lunar surface[103] with a detector with a lower threshold of the order of 50 MeV for the detection of protons showed that the power spectrum of cosmic-ray fluctuations in the frequency interval 10^{-7}–10^{-5} Hz observed on the moon is two to four orders of magnitude higher than the theoretical upper limit. On the other hand, the relation between $P_B(f)$ and $P_j(f)$ was not dealt with completely accurately in Ref. 27, and the result was a theoretical overestimate of $P_j(f)$. Furthermore, comparison of the shape of the spectrum found from the measurements of the cosmic-ray intensity on the lunar surface[103] with the corresponding spectra calculated from ground-based data for quiet times showed that the results agree well at $f \leqslant 10^{-5}$ Hz, within the corresponding errors.

In summary, analysis of recent research leads to the conclusion that the most likely sources of the fluctuations of the cosmic rays both on the earth's surface and in interplanetary space are fluctuations of the interplanetary magnetic field. At frequencies above $5 \cdot 10^{-5}$ Hz, the most important sources are probably magnetosonic waves excited by the fronts of large-scale perturbations of the solar wind. The amplitudes of the fluctuations associated with the scattering of cosmic rays by the magnetic inhomogeneities of the solar wind during the generation of fast particles on the sun could be no greater than a few tenths of 1%.

There have been several unsuccessful attempts to trace the time evolution of the appearance and development of fluctuational phenomena in the cosmic rays,[104] and even the fluctuations themselves have escaped detection. To a large extent, this situation can be blamed on an unsuccessful arrangement of the measurement apparatus (Dhanju and Sarabhai[52,53] have shown that the fluctuation amplitudes fall off sharply with increasing geomagnetic cutoff rigidity, to values of the order of 0.005%) and also on imperfections of the experimental procedure. Considerable assistance in resolving the question of the relationship between fluctuations of the interplanetary magnetic field and fluctuations of the cosmic rays has come from a study of cosmic-ray events in late 1977 (Refs. 86, 89, 105, and 106).

In a study carried out to distinguish structural features in the power spectra of fluctuations in the solar cosmic rays before flares, the preflare periods were partitioned into three intervals[107]: a first interval including the time up to the beginning of the preflare increase in the fluxes of low-energy solar particles (the quiet period), a second including the preflare increase in low-energy particles, and a third corresponding to a flare of fast particles in the initial phase of the decay.

The normalized sampling power spectra of the fluctuations of the proton and electron fluxes which were calculated for these intervals are shown in Fig. 9 in October (a), November (b), and December (c) 1977. The Roman numerals specify the time intervals. The vertical error bars are the 95% confidence intervals. The initial data files were filtered by means of Gaussian and first-difference filters. Several conclusions can be drawn from a study of these spectra:

—All the spectra have peaks differing significantly from adjacent peaks corresponding to fluctuations with periods of 10–20 min for the filtered series (Fig. 9, a and b) and 20–25, 30–40, 50–60, and 90–100 min for the original data files. These peaks are most obvious for protons during time interval III.

—All the spectra are characterized by fluctuations with periods of the order of 12–15 min, whose amplitudes decrease significantly in comparison with those of fluctuations at the other frequencies as the time of the flare approaches. The fluctuations at the other frequencies, which are low under quiet conditions, increase before a flare and are significantly suppressed during a flare. The time evolution of the 15-min fluctuations is somewhat at odds with that of the fluctuations at the other frequencies. Specifically, although the reliability of the peaks which were found does not exceed the 95% confidence interval for many of the periods, the calculations of the power spectra for quiet conditions nevertheless describe a decrease in the amplitudes of all the fluctuations (at frequencies above 10^{-4} Hz) except the 15-min fluctuations. The fact that the time evolution of the 15-min fluctuations is at odds with that of the other fluctuations seems to imply that different mechanisms are operating to give rise to these fluctuations. If the appearance of the fluctuations at the other frequencies is a result of the scattering of charged particles of the cosmic rays by random inhomogeneities of the interplanetary magnetic field, then it would be difficult to see how inhomogeneities of only one period (only one characteristic dimension), significantly greater than the others, could arise during quiet time intervals. We thus have strong support for a relationship between the 15-min fluctuations and the solar activity, especially since 15-min oscillations have been discovered in active regions on the sun itself on the OGO-8 space vehicle. However, this is a question of interpretation, to which we will return below.

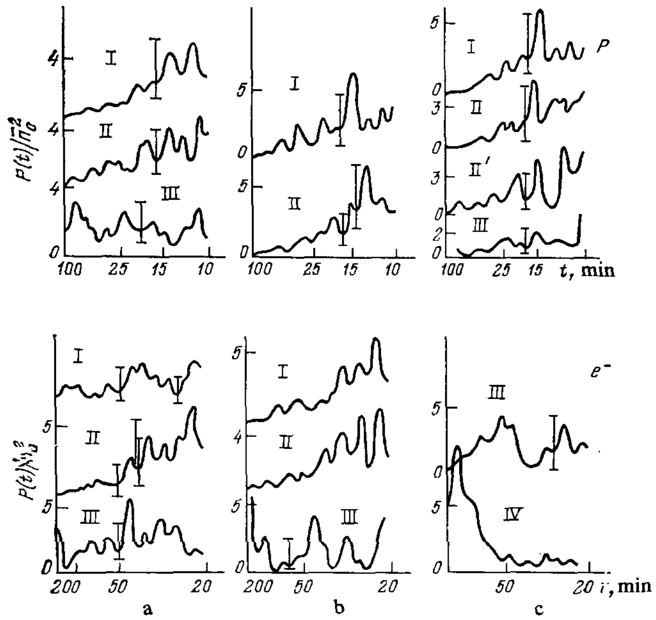

FIG. 9. Spectral characteristics of the proton and electron flux densities on the space vehicle Prognoz-6 for quiet and perturbed times in September, November, and December 1977 (Ref. 107).

For several of the events in this analysis, particularly for electrons during time intervals III, we see fluctuations with periods longer than those of the other fluctuations. For all the spectra, the peaks in the spectrum shift downward along the frequency scale during flares, in good agreement with the ground-based data, more precisely, with the results calculat-

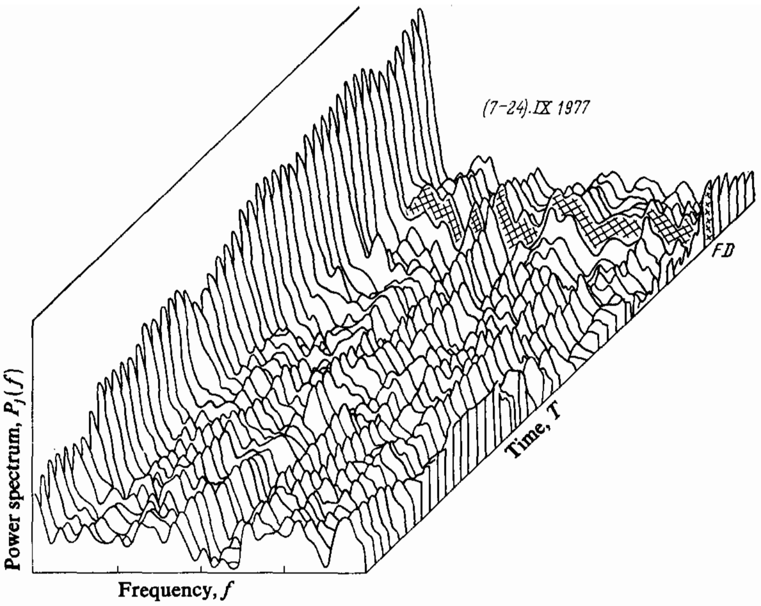

FIG. 10. Power spectra of the fluctuations in the intensities of the neutron and overall components of the cosmic rays for 7–24 September 1979 (Ref. 109).

ed on the cosmic-ray fluctuations from data detected on the earth on 12 November, 22 November, 27 December 1977, and 30 April through 7 May 1978. Figure 10 shows power spectra of the fluctuations of the neutron and total components for 7–24 September 1977. These fluctuations have several prominent peaks. It is particularly easy to follow the growth of fluctuations with periods of the order of 20 and 30–40 min for the events of 12 October 1977, 27 December 1977, and 30 April 1978. For the spectra corresponding to 22 November and 7 May, the high-frequency peaks above $5\cdot10^{-4}$ Hz were not observed as clearly.

A comparison of the spectral estimates obtained for the solar cosmic rays with the corresponding estimates for galactic cosmic rays in ground-based observations and a study of the time evolution of the appearance and development of these estimates reveal good agreement: In both the ground-based measurements and the observations on the space vehicle we can see prominent peaks which, aside from the 15-min peaks, do not exceed a 90% or 95% confidence interval under quiet conditions and which correspond to a broad range of fluctuations. The existence of a complex, rapidly varying picture in the power spectra is of course a hindrance in the processing and analysis of the experimental data. Frequently, after extensive calculations of spectra have been carried out, and several conclusions of apparently universal applicability have been drawn about the behavior, an event will occur for which the results of the calculations do not conform completely to the established results. Nevertheless, the results obtained in the experiments on the vehicles Prognoz-6, Meteor-2, Apollo 14, and several others indicate statistically that fluctuations of the cosmic rays are a possible measure of the state of the interplanetary medium.

5. ORIGIN OF THE COSMIC-RAY FLUCTUATIONS

As we stated at the beginning of this review, the sources of the fluctuations in the cosmic rays observed at the earth's surface can be classifed in five groups: fluctuations associated with acceleration processes on the sun and in interplanetary space; fluctuations originating from oscillatory processes on the sun (in the solar corona, upon escape from the solar quasiconfinement); fluctuational processes during the propagation of the charged particles of the cosmic rays in interplanetary space (the scattering of charged particles by random inhomogeneities of the interplanetary magnetic field and shock waves) and, finally, the fluctuations associated with short-period oscillations in various properties of the earth's magnetosphere and atmosphere.

Detailed experimental studies[5,22,28–30,41–43,52,53,60] have shown that the short-period oscillations of atmospheric properties (the pressure, the temperature, and the humidity) could not be the sources of the observed fluctuations in the cosmic rays. A detailed analysis of 5-min values of the pressure over the intervals February–September 1978, September–October 1979, April–June 1980, and March–September 1982 shows that the power spectra of the fluctuations in the pressure and in the ground-level temperature in the frequency range $10^{-4} \leqslant f \leqslant 1.7\cdot10^{-3}$ Hz are distinguished by the essentially complete absence of prominent peaks.[22,28] (Even at those few times at which peaks are observed, their amplitudes are such that they could cause cosmic-ray fluctuations with amplitudes no greater than[108,109] 0.005–0.01%. As for atmospheric variations in the frequency range $f \leqslant 10^{-4}$ Hz, we note that the corrections to the cosmic-ray data completely eliminate this contribution.[108])

Attempts to explain fluctuational phenomena in the cosmic rays on the basis of temperature fluctuations at various heights also find little support, since the pronounced inertia of the atmosphere essentially prevents observation of rapid temperature changes.[2,39,45] The several instruments whose results have been used to find the power spectra of the cosmic-ray fluctuations (in particular, neutron supermonitors) do not have such a significant temperature effect.[39]

As for fluctuations of the earth's magnetic field and magnetosphere as sources of the observed cosmic-ray fluctuations, we note that although these fluctuations and their amplitudes do correlate with fluctuations of the magnetosphere and the geomagnetic field[60] the appearance of significant fluctuations and the simultaneous increase in the index K_p probably have a common source: perturbations of the interplanetary medium near the earth. This seems particularly obvious since a study of the fluctuations at stations with different geomagnetic cutoff rigidities reveals that the fluctuation amplitude increases with decreasing rigidity.[52,53] This effect stems from, first, an increase in the fraction of relatively low-energy particles and, second, the insignificant contribution of the short-period changes in the geomagnetic and magnetospheric properties to the observed cosmic-ray fluctuations (according to the measurement data, the rigidity dependence of the amplitude of the cosmic-ray fluctuations is of the order of R^{-1}). Calculations show that the maximum amplitudes of the cosmic-ray fluctuations which could be caused by fluctuations of the magnetospheric and geomagnetic properties as a series of fluctuations are a few tenths of 1%. We should point out that everything we have said refers to particles with energies up to 1 GeV. As for fluctuations of the high-energy particles of the cosmic rays which are detected by neutron monitors and telescopes, we note that the effects on these fluctuations of variations in the geomagnetic field and the magnetosphere would be substantially lower (less than 0.01–0.03%).

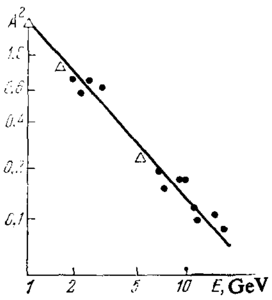

FIG. 11. Energy dependence of the amplitude of the cosmic-ray fluctuations.[61,109,114]

In summary, a detailed study of the cosmic-ray fluctuations and a joint analysis of these fluctuations with various properties of the atmosphere, the magnetosphere, and the geomagnetic field show that the decisive role in the appearance and growth of fluctuational phenomena in the cosmic rays is played by processes in the first three of the five groups defined above. In other words, at least most of the fluctuations in the cosmic rays are of extraterrestrial origin, so that all the theoretical calculations are justified.

According to Refs. 41, 42, 98, and 110–112, the power index of the cosmic-ray fluctuations varies between 1.1 and 3.4 over a broad frequency range with a change in the nature of the time intervals being analyzed (from quiet to disturbed). The total power in the spectral band 10^{-6}–10^{-4} changes by a factor of more than three in 3–4 months.[61,112] A study of the variability of the power spectra of the cosmic-ray fluctuations over the frequency range $10^{-5} \lesssim f \leqslant 10^{-2}$ Hz can yield valuable information on the modulation mechanism.[27,55,113] Extremely important in this connection is a study of the energy dependence of the amplitude of the cosmic-ray fluctuations which has been carried out on the basis of data obtained on the cosmic-ray intensity at the stations at Tixie Bay and Yakutsk[61] and also at Moscow, Nal'chik, and Bologna.[114] Figure 11 shows the energy dependence of the square of the amplitude of these 7-h variation during the events in August 1972, April–May 1978, and September 1979. The fluctuation amplitudes are seen to increase with decreasing energy, suggesting that the observed fluctuations have a source outside the magnetosphere.[61] The time evolution of the frequency spectrum of the cosmic-ray fluctuations observed during Forbush decreases[56–58,61,110,111] accompanied by magnetic storms suggests an extraterrestrial source—interplanetary shock waves—as one of the most likely mechanisms for the formation of the fluctuations. Comparison of the power spectra of the cosmic-ray fluctuations and measurements of the interplanetary magnetic field reveals a good correspondence in the periods of the observed fluctuations. In turn, this agreement explains the appearance of fluctuations in the cosmic-ray intensity. They are caused by quasiperiodic oscillations of the magnetic field in shock waves, as has been pointed out by Kozlov: "The appearance of fluctuations in the cosmic-ray intensity primarily in shock waves of the piston type can be explained by the circumstance that it is in piston shock waves that we have a relatively pronounced compression of the medium and simultaneously a decrease in the diffusion coefficient." [61] Estimates of the magnitude of the fluctuations expected in the cosmic rays[56–58] agree well with calculations of the cosmic-ray intensity spectra during the passage of flare-associated shock waves, so that we can draw several conclusions regarding the role played by oscillatory structures in the magnetic field of the shock waves in the formation of fluctuations. The amplitude of the field oscillations in piston shock waves frequently exceeds the amplitude B_0 by a factor of tens, and the charged particles of the cosmic rays entering the effective range of the magnetic perturbation of a piston shock wave begin to be reflected. This reflection gives rise to fluctuations at the same frequencies.[115,116] Furthermore, the pronounced regularization of the field which is observed during the passage of intense shock waves is seen as a significant shift of the peak in the fluctuation power spectrum down the frequency scale, meaning that there are essentially no small-scale inhomogeneities in the interplanetary magnetic field (see the measurements on 8 December 1982 in Fig. 12). Comparison of the measured spectra of fluctuations in the cosmic rays and the field[117] during the events in August 1972 completely confirms the conclusion (reached in a study of the dynamic spectra of cosmic-ray fluctuations[61]) that there is an increase in the scale dimension of the inhomogeneities (of the turbulence). In turn, the regularization of the field should lead to a hardening of the cosmic-ray spectrum.[118–122] During quiet periods (without any significant perturbations of the interplanetary medium), on the other hand, the spectra of cosmic-ray fluctuations have a broad set of peaks in essentially all frequency ranges, because the interplanetary magnetic field has become very turbulent, i.e., because of the presence of inhomogeneities of essentially all

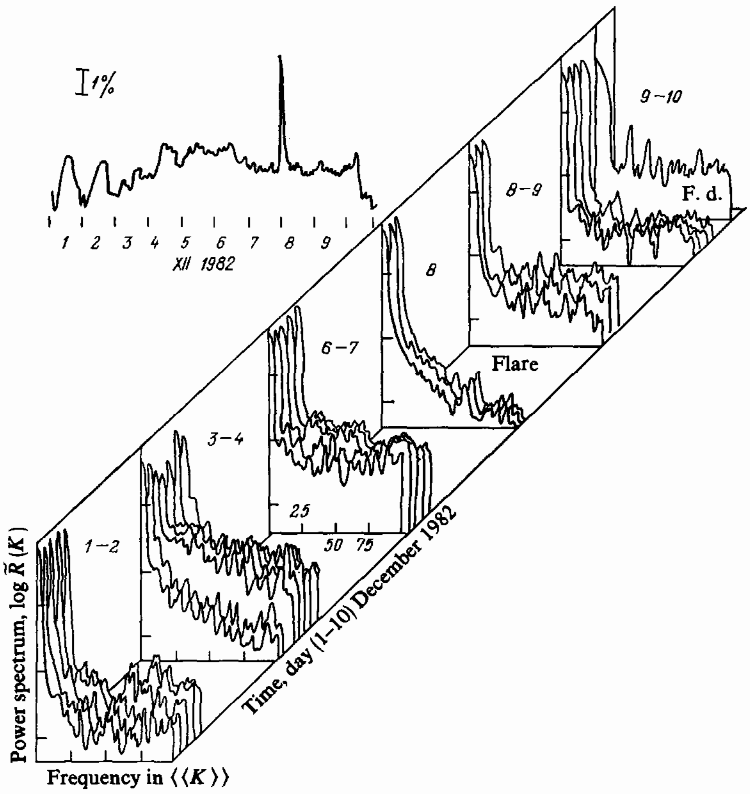

FIG. 12. Dynamic power spectrum of the intensity fluctuations of the overall cosmic-ray component in December 1982 for the flare of 8 December and the Forbush decrease of 12 December.

scale dimensions.[122,124] Most of the inhomogeneities (with scale dimensions of the order of 10^{10}–10^{12} cm) are tangential shocks separating fibers of the solar wind. The force tubes of the interplanetary magnetic field intertwine, forming a complicated structure whose field is directed perpendicular to the earth-sun line. The spectrum of inhomogeneities is of power-law form, $dh^2/dk \sim k^{-\gamma}$, where h is the random magnetic field, k is the wave vector, and γ is the spectral index, which varies under actual conditions (in a quiet medium) from 1.1 to 2.0 because of variations in the slope and power of the spectrum of inhomogeneities for various conditions in the interplanetary medium.[61,125] The scattering of charged particles by single inhomogeneities[123] changes the direction of the particles by small angles. Using the dependence of the transport range on the rigidity and the nature of the field,[124] and determining the scale dimensions of the inhomogeneities from data on cosmic-ray fluctuations, we can determine not only the frequency distribution of the sizes of the inhomogeneities of the interplanetary field but also the frequency distribution of distances between these inhomogeneities.

Analysis of the power spectra of cosmic rays under quiet conditions (according to data from the neutron supermonitor and the scintillation telescope from the stations of the IZMIRAN Institute for September 1978, April–May 1979, and 3–5 December 1982; Fig. 12) shows that at average values of all the parameters the value of B_0 and the power spectrum of the interplanetary magnetic field agree well with both the available data on the field and the general understanding of the spectrum of inhomogeneities of the interplanetary magnetic field under highly turbulent conditions. The studies which have been carried out show that the source primarily responsible for the appearance of the observed statistically significant fluctuations in the cosmic-ray intensity is the scattering of charged particles by random inhomogeneities of the interplanetary magnetic field. The regularization of the field (during intense solar flares, interplanetary shock waves, etc.) leads (first) to the appearance of significant peaks in the spectra, exceeding at least the 90% confidence interval, and (second) a shift of these peaks down the frequency scale because of an energy pumping from high-frequency oscillations of the field down the spectrum. Since the change in the spectra begins at least a few hours before the onset of the perturbation of the interplanetary medium near the earth, the fluctuations of the cosmic rays can serve as a forewarning of a shock wave approaching the earth.[61]

As for the second source of cosmic-ray fluctuations (oscillation and acceleration processes on the sun), we note that data on its operation have been acquired both from a study of fluctuations of the electromagnetic component of the solar radiation and from a study of the fluctuations of solar activity and of the magnetic fields in the solar atmosphere. Observations of the temporal variations in the magnetic fields, sunspots, and the intensity of hydrogen flocculi at Ussuriĭsk[126–128] have revealed statistically significant oscillations with a period of the order of 20–40 min similar to the oscillations observed in data on the radio emission at $\lambda = 3$ cm (Refs. 82 and 129). The sensitivity of solar-measurement methods has now been refined to the level that it has now become possible to measure the natural oscillations of the sun. Data on two oscillation modes, with periods of the order of 40–50 and 160 min, which agree well with the results of a spectral analysis of the intensity of solar cosmic rays during flares, are reported in Refs. 130 and 131. Fluctuations with periods of the order of 160 min are present in the power spectra essentially whenever the changes involve only the amplitudes of these fluctuations, in indirect support of Ref. 130. Study of intense chromospheric flares has shown that the overwhelming majority of proton flares are preceded by an intense buildup of radio fluctuations, which begins a day before the flare and which causes an increase in the amplitude of the 20–60-min fluctuations by a factor of 10–30 by the time of the flare. A similar picture is observed in the solar and galactic cosmic rays. The 5-min data from the continuous measurements of cosmic rays by the neutron supermonitor at the Tixie Bay station have been used to study 132 fluctuations of the cosmic rays during 11 large events in which relativistic protons were generated in solar flares: 28 January 1967, 25 February 1969, 24–25 January and 1–2 September 1971, 7 August 1972, 29 April 1973, 30 April 1976, 22 November 1977, 7 May and 23 September 1978, and 12 October 1981. All the observational data were first corrected for the barometric effect. For each flare, an analysis was carried out over four 8-h time intervals selected in the following way: 1) a day before the flare, 2) 12 h before the flare, 3) during the flare, 4) a day after the flare. For all events it was found that a day before the intensification of the flux of solar cosmic rays from the chromospheric flare pulsations are observed in the cosmic rays with typical periods of 30–40 and 60–90 min; for certain flares, pulsations with periods of 120–160 min are also observed. A day after the flare, no fluctuations with prominent periods are observed. If the changes which occur in the spectra during Forbush decreases (perturbations of the interplanetary medium near the earth which begin a significant time after the flare on the sun) can be explained in a quite simple way,[109–111,114] in the case of flare events this advance feature in the cosmic rays can be explained in terms of a significant increase in the transport range for scattering of particles under conditions of a highly regularized field. Indirect data indicate such an increase.[133] It should be noted that the observed fluctuational effects (effects occurring in advance of events and changes in spectrum) retain their properties even when flares (increases) and Forbush decreases are not seen clearly in the cosmic rays themselves. A study of fluctuations thus provides a remarkable tool for diagnostics of the interplanetary medium at distances of 10^{11}–10^{13} cm from the earth or even farther, according to recent studies.[134,135]

6. THEORETICAL WORK ON FLUCTUATIONAL PHENOMENA IN THE COSMIC RAYS AND THEIR POSSIBLE RELATIONSHIP WITH PROCESSES IN THE INTERPLANETARY MEDIUM

Extensive measurements of the interplanetary medium[136] carried out on space vehicles have shown that the interplanetary magnetic field has a basic structure which is approximately spiral, on which various types of perturbations are superimposed. Kovalenko[136] has stated that "these perturbations are caused by shocks and waves in the plasma of the solar wind, by an anisotropy and a spatial inhomogeneity of the velocity of the solar wind,[137] and by a transport of the transverse component of coronal magnetic fields,[138] and they reflect dynamic processes at the sun and in the interplanetary medium." Fluctuations of the interplanetary magnetic field with periods ranging from several minutes to several hours are caused primarily by waves and shock, while slower changes are associated with interactions between streams and long-period Alfvén waves. Certain small-scale fluctuations may arise from the interaction of fronts or boundaries of streams moving at different velocities. Several fluctuations may arise from the transport of small-scale inhomogeneities out of the corona along with the plasma of the solar wind. The flow of inhomogeneities from the sun can be described in general as consisting of three components: 1) a permanent, almost symmetric part, whose intensity may depend in some way on the solar activity level, but which is not directly related to active formations; 2) a recurrent component consisting of long-lived corpuscular fluxes which are associated with sunspots and which cause magnetic storms with a gradual commencement near the earth; and 3) a nonrepeating component which consists of isolated ejections of magnetized plasma from intense chromospheric flares, which cause magnetic storms with a sudden commencement and which generally give rise to statistically significant fluctuations in the interplanetary magnetic field and the cosmic rays.

A study of various effects in the solar wind itself is intimately related to the nature of these fluctuations and their variations over heliocentric distance. Furthermore, it is quite clear from the experimental results that the fluctuations of the interplanetary magnetic field significantly determine the cosmic-ray propagation conditions and are responsible for various effects seen in the cosmic-ray intensity at or near the earth. This assertion is confirmed by a study of the transport range for the scattering of cosmic rays, which is determined by the intensity of the scattering of cosmic-ray particles by inhomogeneities of the interplanetary magnetic field: Specifically, experiments show that the transport range for the scattering of solar cosmic rays does not increase with distance from the sun[139] (we would expect it to do so if all the inhomogeneities are produced along with the solar wind and then spread out radially from the sun; on the contrary, it decreases. Consequently, a significant fraction of the inhomogeneities appears as the solar plasma moves away from the sun, as the result of the continuous development of various types of plasma instabilities, and from the nature of the changes in the power spectrum of the fluctuations in the cosmic-ray intensity we can draw conclusions about the structure of the interplanetary magnetic field.

The study of fluctuational phenomena in the cosmic rays is actually broken up into several completely independent problems involving the appearance and development of these fluctuations as a function of various processes in interplanetary space. Theoretical methods for dealing with these fluctuations have now become the subject of an extensive literature.[6–25] Fluctuations of the distribution function of the cosmic rays were first studied by Shishov[6] under conditions such that the Larmor radius of a particle in a random field is much longer than the correlation radius of this field.

When this approach is taken, one can ignore the effect of the regular magnetic field on the motion of the charged particles, and the scattering of particles by random inhomogeneities of the magnetic field is determined by the characteristics of the correlation tensor, such as the mean square random field H^2 and its correlation radius L_c.

Dorman and Katz[7-9] have studied fluctuations of the cosmic-ray distribution function for the case in which there is a strong regular magnetic field against the background of random inhomogeneities, so that the Larmor radius of a particle is much shorter than the correlation radius of the random field. It should be noted that the studies in Refs. 7-9 were carried out for particles with energies of the order of 1-100 MeV, so that those theoretical results cannot be applied to the cosmic-ray fluctuations observed at the earth in the data from neutron monitors and scintillation telescopes, which detect particles with effective energies of 3-50 GeV.

A theory describing the fluctuations of cosmic rays with energies close to those observed in actual experiments ($\gtrsim 1$ GeV) was first set forth in the papers by Owens and Jokipii. Working from a kinetic equation, they analyzed the motion of charge particles in a stochastic magnetic field with a nonzero mean value.[10-12] They analyzed in detail the resonant interaction of the particles and the field and also effects associated with nonlinear terms in the kinetic equation. From the solutions which they derived they found a spectrum of interplanetary fluctuations of the cosmic rays, with allowance for the anisotropy of the flux.[27] They showed that the cosmic-ray fluctuations $P^j(f, \mu, W)/j_0^2$ with energies of the order of 1 GeV are caused by fluctuations of the interplanetary magnetic field, $P_\perp^B(f)/B_0^2$, with a mean field B_0:

$$\frac{P^j(f,\ \mu,\ W)}{j_0^2} = C(f,\ \mu)\,\frac{P_\perp^B(f)}{B_0^2}\,(\delta_\parallel)^2,$$

where $\delta_\parallel$ is the anisotropy of the cosmic-ray flux, and the parameter $C(f, \mu)$ reflects the nonlinear effect near resonant frequencies and depends on the solar wind velocity V, the pitch-angle (μ) distribution of the particles, the resonant cyclotron frequency ω_0, and the angle (φ) between the solar wind velocity $\mathbf{V}$ and the lines of force of the magnetic field B

$$C(f,\ \mu) = \frac{(1-\mu^2)\,\omega_0^2}{[(2\pi f\omega/V\cos\varphi)-\omega_0]^2+\omega_0^2\varepsilon^2}.$$

Calculations carried out on the basis of data from the Alert station show that the best agreement between the fluctuations of the cosmic rays and those of the field is observed for the B_θ field component (the correlation coefficient is of the order of 0.45 ± 0.08, in contrast with 0.17 for the component B_φ). The reason for this circumstance is that the scattering of charged particles of the cosmic rays by random inhomogeneities of the interplanetary magnetic field is important for ground-based observations for frequencies $f > 5\cdot10^{-6}$ Hz; at frequencies $f < 5\cdot10^{-6}$ Hz, the sector structure of the interplanetary magnetic field and long-period variations of the cosmic rays themselves begin to play the decisive role. A comparison of the results found here with the results of studies of the interplanetary magnetic field[16-21] shows that this partitioning of the spectrum is determined to a large extent by the shape of the spectrum of magnetic inhomogeneities in interplanetary space near the earth. Calculations on cosmic-ray fluctuations[22,23] at frequencies $f < 10^{-5}$ Hz completely confirm the conclusions reached in Ref. 27 regarding the difference in the nature of the fluctuations in the cosmic rays in the two frequency ranges. The theoretical prerequisites required for this partitioning are satisfied if the flux density of cosmic rays is represented as consisting of several components (in particular, convective and diffusive components):

$$n(t) = n_0 + \delta n_{\text{convec}} + \delta n_{\text{diff}}.$$

The power of the cosmic-ray fluctuations according to this model is

$$\frac{P_{xx}^j(f)}{J_0^2} = \frac{P_{yy}^B}{B_0^2}\,\frac{WV\omega\sin\varphi/6\pi k_\parallel\cos^2\varphi}{f_0^2+f_1^2},$$

from which we conclude that at frequencies $f \sim 10^{-7}$ Hz we would have

$$P(f) = 1{,}55\cdot10^4\ \mathbf{Hz}^{-1}\,[1+(f\cdot10^5\ \mathbf{Hz}^{-1})^{1{,}5}]^{-1}.$$

Comparison of this result with calculations of the power spectra of the cosmic-ray fluctuations in the low-frequency range reveals a completely acceptable agreement. The partitioning of the flux density of cosmic rays into average and fluctuating parts is not arbitrary.[31] It leads to a rather good approximation of the power spectrum of the cosmic-ray fluctuations over the entire frequency range, and it makes it possible to study the relationship between this spectrum and the corresponding spectral characteristics of the interplanetary field. Studying the difference beween the cosmic-ray intensities reaching the earth from the north (N) and the south (S) (the north-south, N-S, asymmetry), Owens showed that the power spectrum of the cosmic-ray fluctuations is[31]

$$\frac{P_{\mathrm{N}}(k)}{n_0^2} = \frac{P_{\mathrm{S}}(k)}{n_0^2} = P_\perp^B(k)B_0^{-2}\left[\delta_z^2+\left(\frac{\omega_0}{kW}\right)^2\delta_x^2\right]^{-1},$$

$$\frac{P_{\mathrm{N-S}}(k)}{n_0^2} = \frac{4\delta_z^2P_\perp^B(k)}{B_0^2}$$

and is determined by not only the spectrum of the interplanetary magnetic field, $P^B(f)/B_0^2$, but also by the anisotropy components δ_x and δ_z of the particle flux.

Figure 13 shows the overall power spectrum of the fluctuations, $P(f) = P_{\text{fl}}(f) + P_{\text{spect}}(f)$, over a broad frequency range. This figure clearly illustrates the twofold nature of the

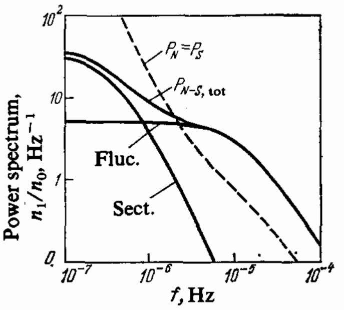

FIG. 13. Theoretical power spectrum of the cosmic-ray fluctuations. The sector structure of the interplanetary magnetic field has been taken into account.[31]

observed spectrum. The existence of this twofold nature presents some extensive opportunities in calculations of the spectra from ground-based data: By measuring the high-frequency part of the spectrum of cosmic-ray fluctuations, one can study the spectrum of inhomogeneities of the interplanetary field. Data on the spectra in the low-frequency region can yield information on the sector structure of the field.

The theory derived on the basis of a kinetic equation provides the most comprehensive description of fluctuational phenomena in the cosmic rays. It is known quite well, however, that the propagation of cosmic rays can be described adequately in the diffusion approximation over a broad energy range of the charged particles. Despite the fact that the particles of comparatively low energies (whose propagation is not described by the equations of the diffusion approximation) undergo the most noticeable fluctuations, the most informative study is a study of the fluctuations at high particle energies (above a few GeV). The propagation of these particles is described satisfactorily by the equations of the diffusion theory. The physical reason for this circumstance is that a particle with a large Larmor radius ($R = cp/ZeH \gg R_c$, where R_c is the correlation radius of the random magnetic field) "sees" a broad spectrum of inhomogeneities of the interplanetary magnetic field, while the low-energy particles, interacting with the high-frequency part of the spectrum of magnetic inhomogeneities, bring information on a comparatively narrow part of the turbulence spectrum of the magnetic field. The fact that the fluctuation amplitudes are small at high energies is offset by the circumstance that ground-based instruments can carry out measurements with good statistics and high accuracy in this energy range.

Since the diffusion is isotropic, and the random magnetic field is statistically isotropic, it is possible to derive a comparatively simple relation[28] between the power spectrum of the fluctuations of the cosmic rays and that of the interplanetary magnetic field:

$$P(f) = \left(\frac{\Lambda \nabla n}{R_c B_0}\right)^2 \left[C_x B(f) + C_y \frac{\cos^2 \lambda}{4} B(f - f_0)\right],$$

where Λ is the transport range of a particle, R_c is the Larmor radius of the particle in the regular magnetic field H_0, ∇n is the gradient of the cosmic-ray density, C_x and C_y are constants (of the order of unity), λ is the asymptotic latitude of the observation station, f_0 is the earth's rotation frequency, and $B(f)$ is the power spectrum of the interplanetary magnetic field, which is assumed to be homogeneous and isotropic. Figure 14 shows power spectra of the cosmic-ray fluctuations calculated from data from the Lomnitskiĭ Shtit and Vostok stations between 15 May and 20 December 1979 (solid curves; part a) and calculated spectra for the values $f_0 = 5\cdot10^{-7}$ Hz, $B(f) = 16\gamma^2$, $B_0 = 5\gamma$, $\Lambda\nabla n/R_c B_0 \sim 1\%$ (b), $f_0 = 5\cdot10^{-7}$ cm/s, and $B(f) = 75°$ (dashed curves). Comparison of the observed spectra of the cosmic-ray intensity with the spectra calculated from the expression of Ref. 28 shows that incorporating the frequency shift due to the earth's rotation (the second term in the expression) leads to good agreement between the experimental and calculated curves. Solution of the inverse problem yields a value of the order of 1.85 for the index of the power spectrum of the fluctuations of the interplanetary magnetic field, in good agreement with direct measurements of the interplanetary magnetic field during the same time interval.

The most convenient expression for practical calculations of the fluctuations spectrum of the interplanetary magnetic field from the observed fluctuations of the cosmic rays can be derived by solving the kinetic equation[13–15,24,25,29,30]

$$\frac{P^j(f)}{j_0^2} = \delta_{\parallel}^2 \langle\langle C_h(f)\rangle\rangle \frac{1}{2}\left(\frac{P^B_{xx}(f)}{B_0^2} + \frac{P^B_{yy}(f)}{B_0^2}\right),$$

where $\langle\langle C_h(f)\rangle\rangle$ represents a term which reflects the nonlinear effect near resonant frequencies, given by

$$\langle\langle C_h(f)\rangle\rangle = \frac{\int_0^1 \int_0^\infty C(R, \mu, f)\, W(R)\, dR\, F(\mu)\, d\mu}{\int_0^\infty W(R)\, dR \int_0^1 F(\mu)\, d\mu},$$

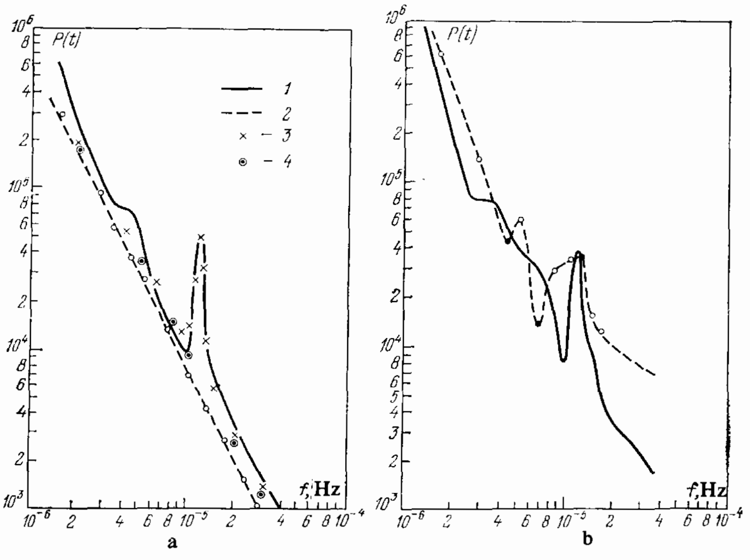

FIG. 14. Power spectra of the cosmic-ray fluctuations.[133] 1—According to data from the Lomnitskiĭ Shtit station; 2—the approximation $R(f) \sim f^{-1.85}$; 3—according to the expression from Ref. 133; 4—without allowance for the diurnal variation.

$W(R)\mathrm{d}R$ are the coupling coefficients relating the cosmic-ray intensity detected at the earth's surface to the intensity of cosmic rays incident on the earth's atmosphere, $F(\mu)\mathrm{d}\mu = \mu^n\,\mathrm{d}\mu$ is the pitch-angle distribution, ε is a dimensionless parameter, and

$$C(R,\ \mu,\ f)=\frac{(1-\mu^2)\,\omega_0^2}{[(2\pi\mu f\omega/V_W\cos\varphi)-\omega_0]^2+\omega_0^2\varepsilon^2}.$$

Taking all the parameters into account, we find an expression for the power spectrum of the cosmic-ray fluctuations which is complicated but quite convenient for calculations:

$$\frac{P_{\text{fl}}(f)}{j_0^2}=\frac{1}{2}\,\delta_{\|}^2\left(\frac{P_{xx}^B(f)}{B_0^2}+\frac{P_{yy}^B(f)}{B_0^2}\right)\frac{\displaystyle\int_0^1\int_{R_c}^{\infty}\frac{(1-\mu^2)(300B_0v/R)^2\,W(R)\,\mathrm{d}R\mu^n\,\mathrm{d}\mu}{\dfrac{2\pi vf\mu}{V\cos\varphi}-\left(\dfrac{300B_0v}{R}\right)^2+\left(\dfrac{300B_0v}{R}\right)^2\left(\dfrac{P_{\perp}^B(f)}{B_0^2}\right)^{2/k}\left(\dfrac{V\cos\varphi}{2\pi\mu}\right)^{2/k}\left(\dfrac{300B_0v}{R}\right)^{2/k}}}{\displaystyle\int_0^1\mu^n\,\mathrm{d}\mu\int_{R_c}^{\infty}W(R)\,\mathrm{d}R},$$

where v is the velocity of the cosmic-ray particles, V is the velocity of the solar wind, and B_0 is the interplanetary magnetic field. It should be noted that this expression can be used to solve only the direct problem: that of determining the power spectrum of the cosmic-ray fluctuations from data on the fluctuations of the interplanetary magnetic field. In order to solve the inverse problem, it is necessary to make an unacceptably large number of assumptions. Nevertheless, the corresponding calculations have been carried out[30] for $\langle B\rangle \sim 5\gamma$, $\langle v\rangle \sim 2.8\times10^{10}$ cm/s^{-1}, $\langle\varphi\rangle \sim 45°$, $\langle V\rangle \sim 5\cdot10^7$ cm/s^{-1}, and $\langle\delta_{\|}\rangle \sim 0.1 - 0.2\%$ for the values $n = 0$, 1, and 2 (Fig. 15). The theoretical spectra of the cosmic-ray fluctuations (the solid curves) and the experimental spectra (the points) agree best with $n = 1$ or 2 for quiet conditions in the interplanetary medium. Similar calculations ignoring nonlinear effects lead to a spectrum (dashed curve) substantially different from the experimental spectrum.

The best way to solve this problem would be to determine the basic characteristics of the interplanetary medium (the magnetic field B_0, the power spectrum of the field fluctuations, and the solar wind velocity V) from data on fluctuations in the cosmic rays. This can be done either by using a cosmic-ray spectrograph[32,33] or by simultaneously using various other cosmic-ray instruments (neutron supermonitors; muon and scintillation telescopes[33–36]). Although the characteristics of the interplanetary medium are not determined very accurately from the data from a variety of instruments at the same station (because of the different energy sensitivities of the instruments), this procedure can be used to find approximate results. It should be noted that this procedure cannot find the separate values of the factors in the product B_0V: In the calculations, data on cosmic-ray fluctuations yield information on the power spectrum of the fluctuations of the interplanetary magnetic field and on the product B_0V. The spectrum of fluctuations of the interplanetary field is given in the power-law form $Af^{-\gamma}$, in good agreement with the observed results, although estimates can be found only over broad frequency ranges. If the intention is instead to study the power spectra of the interplanetary magnetic field in narrow frequency intervals, this calculation algorithm does not describe the presence of prominent peaks in the power spectra of the cosmic rays, so it yields only average characteristics of the field. To find more-accurate characteristics it is necessary to introduce, in the expression relating the fluctuations, a term to describe the fine structure of the spectra of the fluctuations of the cosmic rays and thus of the field, since distinct frequencies also exist in the field fluctuation spectra[39,40]:

$$\frac{P_{\text{fl}}(f_i)}{j_0^2}=\frac{1}{2}\,\delta_{\|}^2\,\langle\langle C_h\rangle\rangle\,\frac{P_{\perp}^B(f_i)+F(f_i)}{B_0^2},$$

where

$$F(f_i)=\begin{cases}0 & \text{for}\quad f_0<f<f_2,\ f_1<f<f_2,\ \ldots,\\ g_i(f) & \text{for}\quad i=0,\ 1,\ 2,\ \ldots,\end{cases}$$

and the f_i are the prominent frequencies with statistically significant peaks in the power spectrum of the cosmic-ray fluctuations. It is especially important to refine the model since the appearance of statistically significant peaks in the power spectra of the cosmic-ray fluctuations generally is evidence of a change in the structure of the interplanetary magnetic field near the earth,[41–43] evidence of the occurrence of perturbations of the interplanetary medium and of the geomagnetic field, and—the most important point—a precursor of approaching shock waves.[61] This type of probing of the interplanetary medium can be carried out continuously at various distances from the earth; the only question is the type of instrument to be used for the observations.

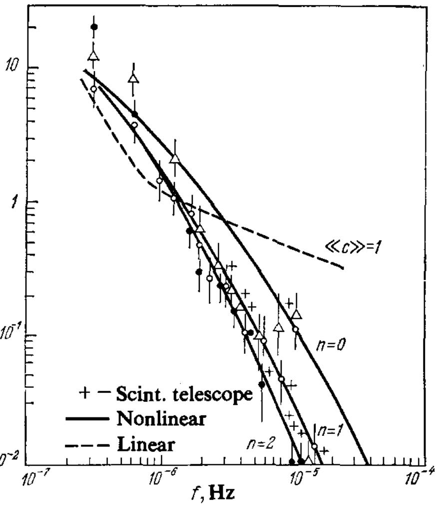

FIG. 15. Comparison of the theoretical and experimental power spectra of cosmic-ray fluctuations[26,30,31] ($\langle\langle c\rangle\rangle = 1$ means $\langle\langle C_h(f)\rangle\rangle = 1$).

7. CONCLUSION

Extensive experiments and calculations have resulted in the development of methods for short-term predictions and diagnostics of shock waves through observations of ground-level fluctuations in the cosmic rays with periods ranging from 12–15 to 420 min. These fluctuations are the ones most sensitive to a shock wave approaching the earth.

As discussed above, it is easy to explain why the effects in the cosmic rays occur in advance of the perturbation of the interplanetary medium: The cosmic rays sense inhomogeneities at a distance equal to their transport range for scattering, i.e., at a distance of the order of 10^{12}–10^{13} cm for the particles which are detected by supermonitors and scintillation telescopes at the earth's surface. The cosmic rays travel at nearly 30 times the velocity at which a perturbation propagates toward the earth, so that information on the approaching perturbation is carried to the earth essentially instantaneously by the cosmic rays—long hours before the perturbation completes its comparatively leisurely voyage to the earth. Since the energies of the cosmic rays detected at the earth stretch over a rather broad range, the distances at which the perturbations approaching the earth will be sensed by the cosmic rays will also span a broad range: By detecting particles of various energies, one can detect inhomogeneities out to several astronomical units.

This effect does not exhaust the possibilities of studying fluctuations. Studies of the power spectra of cosmic-ray fluctuations have revealed that the perturbation level of the interplanetary medium is related not only to the prominent oscillations at certain frequencies but also to the overall spectrum: The slope of the spectrum of fluctuations in the cosmic rays gradually increases to a maximum several hours before the arrival of a perturbation of the interplanetary medium at the earth, remains at this maximum during the perturbation, and then decreases after the perturbation has passed the earth. The slope of the spectrum is at a minimum in a quiet solar wind. Certain features appear in the spectral characteristics of the cosmic rays in advance of solar flares; specifically, the slope of the power spectrum of the cosmic-ray fluctuations changes, and prominent peaks appear in the spectra. These effects, which have been observed in several studies, require further careful investigation. There would be little point in discussing possible mechanisms for these effects (a buildup of solar plasma a day before a flare, an increase in the transport range of particles under conditions of a strong field regularization, etc.) until each change in the spectrum is precisely identified with a specific flare, since in many of the events which have been analyzed the factor causing this change in the spectrum might be either flares preceding that being analyzed or high-velocity fluxes. The effect of these fluxes on fluctuational phenomena in the cosmic rays must be studied in the near future. If the suggested intensification of the spectrum at certain frequencies as sector boundaries of the interplanetary magnetic field pass the earth survives further study (at this point, the observational information on such effects is extremely scanty), the boundary of a high-velocity stream should apparently have observable consequences in the cosmic-ray fluctuations.

We believe that the outlook for the future study of fluctuations in the cosmic rays and for using these fluctuations for diagnostics and predictions will depend on progress in two general directions. First, there is the further development of theoretical work (the kinetic theory of fluctuations; approximations based on models of isotropic and anisotropic diffusion; the theory of fluctuations of atmospheric and geomagnetic origin; and the theory of the appearance of fluctuations during the generation of solar cosmic rays and their propagation in the corona, in interplanetary space, and in the earth's magnetosphere). Second, there is the expansion of experimental research (the detection of fluctuations in the cosmic rays from various asymptotic directions by means of high-precision instruments at the earth's surface; the use of the worldwide network of neutron monitors as a single, global, multidirectional superinstrument; the detection of cosmic-ray fluctuations by means of multidirectional supertelescopes at various depths underground; and the more extensive use of the observed fluctuations in the cosmic rays on balloons, earth satellites, and space vehicles). We will need to refine the methods for analyzing experimental (real-time data analysis by independent methods, used to control each other: spectral analysis, which can furnish information on the existence of oscillations in the raw data and on their amplitude, on the phase shifts between processes, and on coherence spectra; and dispersion and autoregession analysis, which can accurately evaluate the reality of the observed fluctuations and can model the process itself in some approximation). It then becomes possible to solve several important problems of the quantitative diagnostics and prediction of events (of importance to space research and to its applications on the earth) such as intense solar flares, interplanetary shock waves, and perturbations propagating through interplanetary space.

The possibilities of research on cosmic-ray fluctuations have not been exhausted. Quantitative estimates of the state of the interplanetary medium on the basis of observations of cosmic-ray fluctuations on the earth are a task for the near future. Decisive steps in this direction have been taken in the studies by Owens, Jokipii, Krymskiĭ, Katz, Bergamasko, Dolginov, and Toptygin, among others. They have established direct relationships between spectral estimates of the cosmic-ray fluctuations and fluctuations of the interplanetary magnetic field. It thus appears that we will soon be seeing estimates of the state of the space environment of the earth generated just as continuously as cosmic rays are presently being detected. The first steps in this direction have already been taken.

When Victor Hess launched his celebrated balloon flight on 7 August 1912 and thereby founded modern space physics,[140] did he imagine that seventy years later the rays which he discovered would serve as forewarnings of cosmic storms?

[1)] Tests *g* and *h*, like the test for the equivalence of the uncorrelated realizations, have not yet been used in actual analysis programs.

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Translated by Dave Parsons