GEOFISICA INTERNACIONAL

REVISTA DE LA UNION GEOFISICA MEXICANA, AUSPICIADA POR EL INSTITUTO DE GEOFISICA DE LA UNIVERSIDAD NACIONAL AUTONOMA DE MEXICO

Vol. 27 México, D. F., 1o. de abril de 1988 Núm.2

LARGE-SCALE COSMIC RAY FLUCTUATIONS INFERRED FROM THE GROUND-BASED NEUTRON AND IONIZING COMPONENT OBSERVATIONS AND THEIR RELEVANCE TO COSMIC RAY ANISOTROPY

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(Received: September 17, 1986)
(Accepted: December 11, 1986)

RESUMEN

Se estudia el comportamiento del espectro de potencia de las fluctuaciones en la intensidad de los rayos cósmicos para frecuencias menores de 10^{-4} Hz, determinado a partir de las observaciones en superficie de las componentes nucleónica y de ionización. Se hace un intento de describir el espectro de fluctuaciones, usando cambios en el valor de la anisotropía de rayos cósmicos y del espectro de inhomogeneidades del campo magnético interplanetario.

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ABSTRACT

The work treats with the behaviour of the cosmic ray fluctuation power spectrum in the frequency range below 10^{-4} Hz inferred from ground-based observations of the neutron and ionizing components. An attempt is made to describe the observed rearrangement of the fluctuation spectrum using changes in the value of the cosmic ray anisotropy and the rearrangement of the IMF inhomogeneity spectrum.

INTRODUCTION

The fluctuations of the cosmic ray flux detected at the Earth, which cannot be accounted for by fluctuations of the cosmic ray Poisson distribution, were related to the scattering of charged particles by random inhomogeneities of the interplanetary magnetic field (Dorman and Libin, 1985; Blokh *et al.*, 1984; Dorman *et al.*, 1983; Fillisentti *et al.*, 1982; Bezrodnykh and Kuzmin, 1982; Owens, 1974). During quiet periods, when the recorded cosmic ray intensity may be treated as a steady-state and, in a broad sense, as a stochastic process, the power spectrum $P^x(f)$ of cosmic rays with energies of the order of 1 GeV proved to be related (Fillisentti *et al.*, 1982) to the IMF power spectrum $P^B(f)$, in the frequency range $f \leqslant 10^{-4}$ Hz, by

$$\frac{P^x(f)}{j_o^2} = A(f) \frac{P_\perp^B(f)}{B_o^2} \delta^2 \tag{1}$$

where j_o is the mean cosmic ray flux, B_o is the regular magnetic field component, δ is the cosmic ray anisotropy, and A(f) is a dimensionless frequency function containing the resonant cyclotron frequency. To avoid confusion with terminology, we wish to remind that the spectral density, or power spectrum P(f), of a steady-state stochastic process is called the Fourier transform of its correlation function $R(\tau)$

$$P(f) = \frac{1}{2\Pi} \int_{-\infty}^{\infty} e^{-if\tau} R(\tau) d\tau \tag{2}$$

In the absence of resonance $A(f) \sim 1$ and, therefore, if the spectrum $P^B(f)$ is governed by a power law, $P^x(f)$ will also be a power law. In the review by Dorman and Libin (1985) attention was paid to the fact that information about IMF may be derived from the spectral density of cosmic rays. However, the estimation of the cosmic ray spectral density in the periods of interest, with a view of deriving information about the IMF, is faced with serious difficulties. In this case we are dealing with an unsteady-state process which gives rise to distortions of the spectral estimates whose definition (2) is only reasonable in the sense of steady-state processes. For the same reasons, theoretical estimates are also difficult to obtain (Dorman *et al.*, 1985, 1986;

Gulinsky *et al.*, 1985; Bezrodnykh *et al.*, 1982; Kozlov, 1981; Tolba *et al.*, 1981; Sari and Ness, 1970).

METHOD OF ANALYSIS

At present, the application of the periodogram technique and of the Fast Fourier transform has made it possible to obtain numerous estimates of the spectral density of cosmic rays which demonstrate that in the low-frequency range they can properly be described by a power law function. At the same time, the fluctuations (*i.e.* the pronounced peaks in the spectral density) are observed not only in the cyclotron resonance region, but in a broad frequency range (Bezrodnykh and Kuzmin, 1982; Tolba *et al.*, 1981; Owens, 1974). However, the traditional methods for estimating the spectral density used in these works suffer from some fundamental drawbacks. First, the implicit weighting of data required in these methods, when calculating the spectral density estimates, gives rise to additional peaks which are side lobes of the main peak, thereby making the estimates jagged. Second, the methods show a low resolution in frequency. These drawbacks are specially perceptible when working with short data intervals. This situation arises in particular, when analyzing the disturbed periods in which short quasi-steady-state intervals have to be discriminated in data bases.

Recently, however, the spectral density in many problems of physics and technology have been estimated using methods based on simulation of an examined process in terms of a linear parametric model. Experience has shown that these methods allow higher accuracy and resolution, specially for short data intervals (Kay and Marple, 1981). The application of the most general linear autoregressive-moving average (ARMA) model, in such approach, assumes that the examined time series x_n of data may be simulated as

$$x_n = \sum_{s=1}^{p} a_s x_{n-s} + \sum_{k=0}^{q} b_k \xi_{n-k} \qquad (3)$$

where $\{\xi_k\}$ is a sequence of uncorrelated random values with mean $E\{\xi_n\} = 0$ and variance $E\{\xi_n^2\} = \sigma_n^2$. The spectral density of the process $\{\xi_k\}$ is $P(f) = \sigma^2/2\pi$, while the density spectrum $P^*(f)$ of the output process $\{x_n\}$ is related to $P^\xi(f)$ as (see for example Andersen (1976))

$$P^x(f) = \frac{\left|\sum_{k=0}^{q} b_k e^{if(q-k)}\right|^2}{\left|\sum_{s=0}^{p} a_s e^{if(p-s)}\right|^2} \cdot \frac{\sigma^2}{2\Pi} \qquad (4)$$

With such approach, the estimation of the spectral density $P^x(f)$ reduces to the identification of the parameters $\{a_k\}$ and $\{b_k\}$ of the model (3), whereupon $P^x(f)$ can be calculated using (4).

The feasibility of using the ARMA process as a model for a steady-state stochastic process results from the fact that an arbitrary continuous spectral density can be approximated in any way accurately by a rational spectral density of the form (4). The physical evidence of the proper application of such approach to the problem under study is given by the relation (1). The function A(f) may be treated as the transfer function of a linear system connecting the input $P_\perp^B(f)$ and the output $P^x(f)$ in the frequency region. In the absence of resonance, when $A(f) \sim 1$, $P_\perp^B(f)$ and $P^x(f)$ must approach a power law form according to theoretical estimates. This circumstance makes it possible to expect that the (p, q) order of the model necessary for approximating an unknown spectral density P(f) by a rational spectral density of the form (4) would not be high. The expectation was answered in practical calculations. Moreover, a simple AR model, where q = 0 and the p-order is not too high, proves to be sufficient. The parameters of the model (3) may be estimated in many ways, however, from the different methods available for estimating the coefficients, we have selected the modifications of the Levinson-Durbin and Burg algorithms (Key and Marple, 1981).

The procedure followed in the calculations with these algorithms, for disturbed data intervals, is to select the quasisteady-state data intervals superimposed on each other and use them to construct the spectral density estimates. In some cases this technique yields good results, however, in the intervals with rapid rearrangements the spectral density estimates depend strongly on the choice of the interval length. Bearing this in mind, we have developed an approach based on the concept of instantaneous spectral density of an unsteady-state process (Gulinsky *et al.*, 1985).

In case of a process of the type (3), where the coefficients a_s and b_k are assumed to vary with time (within the stability region of the system), the instantaneous (at moment t) spectral density of the unsteady-state process $\{x_t\}$ can formally be determined by

$$P^x(f,t) = \frac{\left| \sum_{k=0}^{q} b_k(t)\, e^{if(q-k)} \right|^2}{\left| \sum_{s=0}^{p} a_s(t)\, e^{if(p-s)} \right|^2} \cdot \frac{\sigma^2}{2\Pi} \tag{5}$$

To estimate the time-dependent coefficients $a_s(t)$ and $b_k(t)$, they can be series expanded in a complete set of functions

$$a_s(t) = \sum_{i=1}^{N} \alpha_{si}\,\varphi_i(t) \;; \qquad b_k(t) = \sum_{i=1}^{N} \beta_{ki}\,\varphi_i(t) \tag{6}$$

Then, given the number N of expansions (6) and the order of the (p, q) model, we may use the method of least squares to calculate the coefficients $\{\alpha_{si}\}$, $\{\beta_{ki}\}$, $s = 1, 2, \ldots, p; k = 1, 2, \ldots, q; i = 1, 2, \ldots, N$ for the selected set of functions $\{\varphi_i(t)\}$. It is important in this case to properly select the set of functions $\{\varphi_i(t)\}$. Relevant experiments have shown that the application of cubic splines yield the best results here.

Let us have a data set $\{x_t\}$, $t = 1, 2, \ldots, M$. We shall treat the AR-model with variable coefficients, *i.e.*, we shall assume that the sequence $\{x_t\}$ may be considered as generated by a process of the form

$$x_t = -\sum_{s=1}^{p} a_s(t)\,x_{t-s} + \xi_t \tag{7}$$

Let the set $\{x_t\}$ be divided into $N < M$ uniform intervals and the coefficients $a_s(t)$ be series-expanded using the known system of cubic splines of defect 1 $B_i(t)$, $i = -1, 0, \ldots, N$ (see, for example, Zavyalov *et al.*, 1980):

$$a_s(t) = \sum_{i=-1}^{N} \alpha_{si}\,B_i(t) \tag{8}$$

Then, to estimate the coefficients $a_s(t)$ in model (7) by the least squares methods we need to find the minimum of the functional

$$\sum_{t=1}^{M} (x_t - \hat{x}_t)^2 \longrightarrow \left\{\alpha_{si}^{min}\right\} \tag{9}$$

using the set of parameters $\{\alpha_{si}\}$, $s = 1, \ldots, p; i = 1, \ldots, N$ where

Therefore, in case of a steady-state AR-model, the problem reduces to solve a set of linear algebraic equations which are, however, of higher dimension. The matrix is inverted by the algorithm which makes use of the property that a matrix becomes much more rarefied when B-splines are used. Being out of the scope of the present work going into finer detail of the procedure used in this approach, we shall only mention that results using it with different test problems have yielded good results.

The procedure used to obtain the spectral density estimates in such approach differs from that described above as follows. The entire $\{x_t\}$ data base is used, while the division into data intervals is associated with the selection of the number N in the expansion (8) which, obviously, must rise when increasing the variation rate of the factors a(t). Thus, the approach permits the entire statistics to be used when constructing the estimates. To obtain a spectral density estimate at any moment t, it is necessary to substitute the values of $a_s(t) = -\sum_{i=-1}^{N} \alpha_{si} B_i(t)$ with the calculated parameters in the expression

$$P^x(f, t) = \frac{\sigma^2}{2\Pi \left| \sum_{s=0}^{p} a_s(t) e^{if(p-s)} \right|^2} \tag{11}$$

which is a special case of (5).

The above-discussed methods for estimating the spectral density were used to analyze the cosmic ray detected data obtained during Forbush decreases. The analysis served two purposes. First, the applicability of the algorithms was verified by real, rather than test, problems. Second, an attempt was made to single out the prominent features of the statistical characteristics of the examined processes during the rearrangement periods which may have been used to construct a theoretical model for diagnosing the given event on the basis of a routine of data processing. Therefore, use was made of cosmic ray data detected at Utrecht from September 7 to 24, 1977 and at Kerguelen from September 18 to 28, 1977. The examined period has already been properly studied, so the results can be controlled safely.

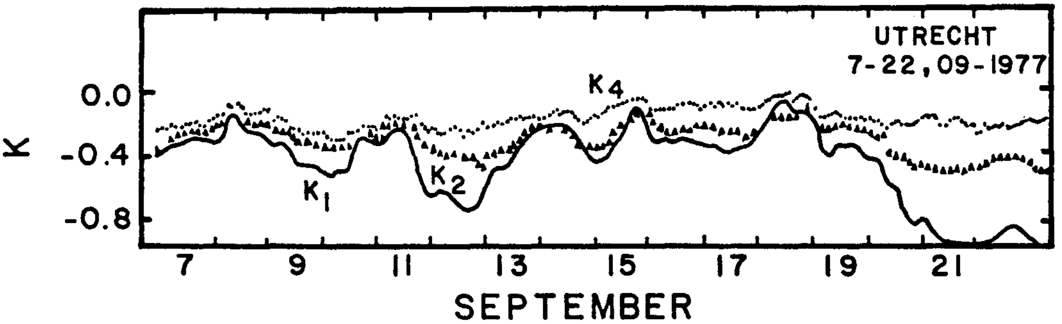
With the same purpose of controlling the results, the calculations were made simultaneously with the above mentioned algorithms. The analysis of the effectiveness of the algorithms has shown that the two approaches yield quite similar results if the length of an analyzed data interval can be properly selected when the steady-state AR-model method (the Levinson-Durbin or Burg method) is used. The advantage of the unsteady-state AR-model was noticeable, for example, when approaching a Forbush decrease commencement point for which the quasisteady-state conditions are difficult to select. At the same time, the results of the analysis, by the unsteady-state AR-model methods, depend not so strongly on the number N of intervals, thus permitting the entire available time series of observed data to be used. As expected, the p order of the model was not high ($p < 10$) in all cases for the given problem.

The first reflection factor is one of the criteria permiting the character of spectral rearrangement to be appraised qualitatively. This factor is estimated in the first step of the Levinson-Durbin procedure and has the meaning of a coefficient in the spectral density expansion (8) of the first order. Fig. 1 shows the behaviour of this first reflection factor inferred from the data obtained at Utrecht from 0005 UT on September 9 to 0000 UT on September 25, 1977. From this figure it can be seen that the absolute value of the reflection factor decreases abruptly at 2335 UT on September 11 and at 1800 UT on September 18, reaches a minimum at 0000 UT on September 9 and 17, and increases afterwards until the commencement of each of the two Forbush decreases. The same pattern was also inferred from studying the first reflection factor on the basis of the Kerguelen data, namely, the decrease began at 0030 UT on September 17, reached a minimum in 10 hours, and increased also by the moment of the Forbush decrease commencement. The irregular behaviour of the reflection factor on September 15 and 16, 1977 is probably due to the complicated dynamics of interplanetary space during that period. The increase of the absolute value of the reflection factor was observed during the cosmic ray Forbush decrease commencements on September 12 and 21. The reflection factor behaviour is in good agreement with the spectral density rearrangement pattern inferred from the Utrecht (Fig. 2a) and Kerguelen (Fig. 2b) data. The spectral densities in the figures are shown with a 12-hour shift for Utrecht (from 0005 UT on September 19 to 0000 UT on September 21). The time axis is directed upwards. The analysis of the spectral density on the basis of the Utrecht data has shown the following pattern of the density rearrangement. Before September 19, the spectral density exhibited peaks at the frequencies 6.67×10^{-4} and 1.33×10^{-3} Hz, while the low-frequency spectral density was of a power-law form. Two days before the Forbush decrease the spectrum is rearranged to a form resembling a "white-noise" spectral density (curve 3 in Fig. 2a). The same pattern holds also for Kerguelen (curve 1 in Fig. 2b corresponds to the same moment as curve 3 in Fig. 2a). From 0000 UT on September 19 onwards, the spectra calculated for the two stations again show the peaks (though of larger amplitudes) at the same frequencies 6.67×10^{-4} and 1.33×10^{-3} Hz.

The results obtained seem to agree with the model for cosmic ray propagation in interplanetary space under quiet conditions and during disturbances in the interplanetary medium.

The results of the analysis and their comparison with the IMF data have shown that the proposed methods make it possible to diagnose the approach to the Earth of a shock wave responsible for the Forbush decreases a day before their commencement. However, the results obtained need being examined further using data from other stations.

(a)



(b)

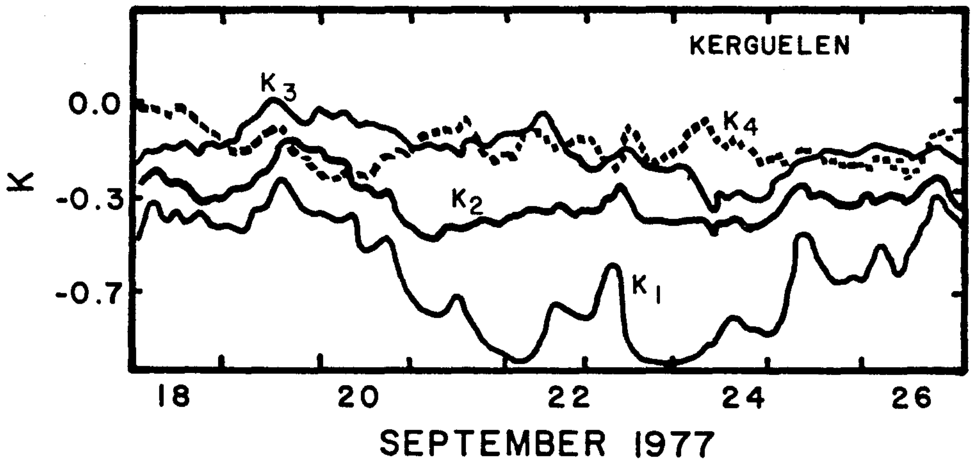


Fig. 1. Behaviour of the reflection factors K inferred from the Utrecht (a) and Kerguelen (b) data for the Forbush decrease periods on September 1977.

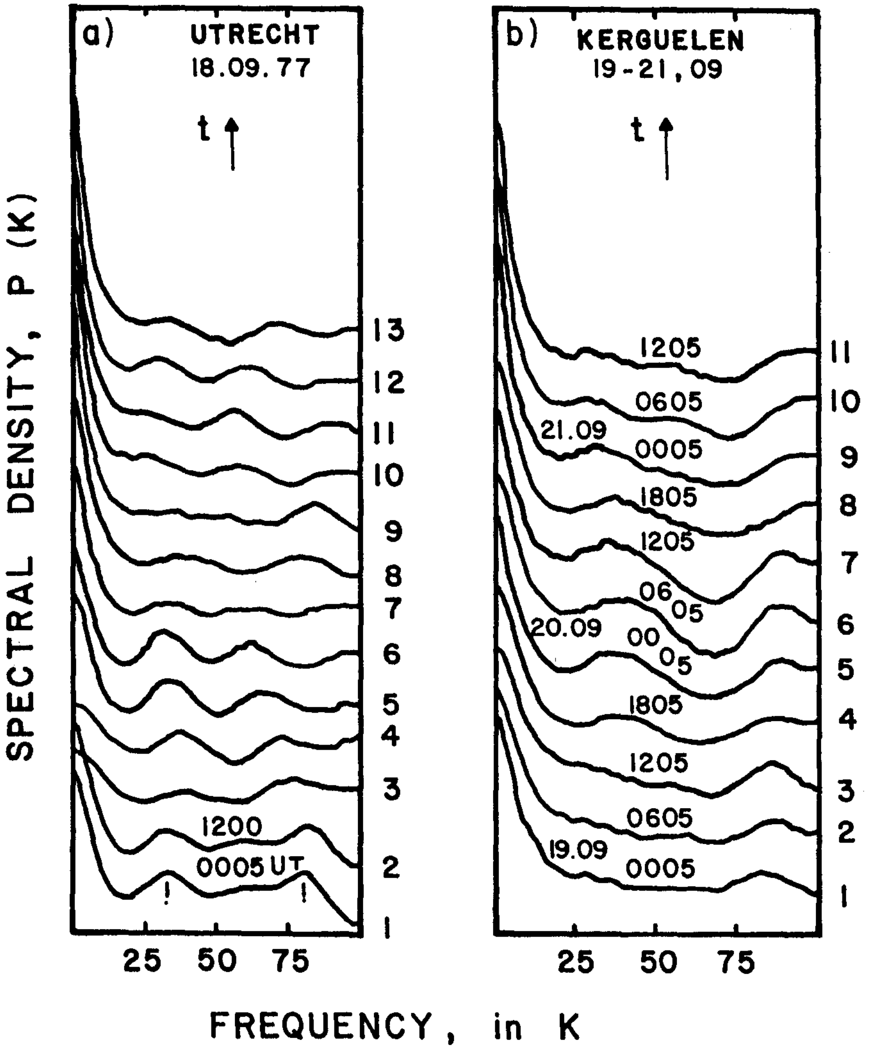


Fig. 2. Instantaneous spectra inferred from the cosmic ray neutron component data obtained at Utrecht (a) and Kerguelen (b). Frequency in 1/60 000 Hz.

COSMIC RAY FLUCTUATIONS FROM GROUND-BASED OBSERVATIONS

The large-scale fluctuations of the solar wind velocity constitute the main source of the galactic cosmic ray fluctuations observed on the Earth in the 10^{-7} - 10^{-4} Hz band. The studies of the spectral characteristics of the cosmic ray fluctuations (with periods from hours to two weeks) made by Dorman and Libin (1985), Fillisentti *et al.* (1982), Dorman *et al.* (1983), Blokh *et al.* (1984) and Bezrodnykh and Kuzmin (1982) have revealed some interesting regularities. Fillisentti *et al.* (1982) used the 1973-74 observed data obtained with a muon telescope and the ionization chamber under 10 cm of lead shielding at Huancayo and Fredericksburg and with the neutron monitors at Climax, Deep River and Huancayo to study the large-scale cosmic ray fluctuations in the 0.9 - 1.3 x 10^{-6} Hz band. The unambiguous relationship of the observed fluctuations (with amplitudes of about 15 - 3.5% for different instruments) to the two-sectorial IMF structure was obtained, in good agreement with Owens' calculation results (Owens, 1974). The calculations of the 10^{-6} - 10^{-4} Hz cosmic ray intensity fluctuations by Dorman *et al.* 1983), Blokh *et al.* (1984) and Bezrodnykh and Kuzmin (1982) have shown that, at least from 2 x 10^{-5} Hz to 5 x 10^{-4} Hz, the spectra can be properly described by a power law $P(f) \sim Af^{-\gamma}$, where γ varies from 1.5 to 3.5 - 4.2 depending on the interplanetary medium state, on the presence of recurrent disturbances in the medium and on the spectrum of the IMF inhomogeneities. The latter dependence is extremely important because Sari and Ness (1970) showed that the magnetic inhomogeneity spectrum in the 1.4 x 10^{-4} - 2.3 x 10^{-6} Hz band could be described by a power law with spectral index $\gamma = 5/3$ ($\gamma = 2$ in the higher-frequency band), while the relationship between the fluctuation spectra of cosmic rays and IMF is sufficiently uniform (Owens, 1974). Sari and Ness (1970) have shown that it is essential that the analysis and calculations of the large-scale cosmic ray fluctuations should be made allowing for the longitudinal IMF component B whose fluctuations with periods of 6.75, 9, 13.5 and 27 days are more than one order in excess of the fluctuations in the transverse component of the IMF ($B_\perp$). Examining the power spectra of the IMF fluctuations with periods from 40 min to several days has demonstrated a substantial decrease of the B fluctuation amplitude, although in this case such fluctuations may give rise to cosmic ray fluctuations with amplitudes of about 0.2 - 0.3% in the high-energy side of the spectrum.

The numerous calculations of the spectral cosmic ray characteristics made on the basis of 5-min, hourly, bihourly and daily-mean values of the intensities of the cosmic ray neutron, muon and ionizing components by Kozlov (1981 a, b) and Gulinsky *et al.* (1985) have revealed a complicated and rapidly changing pattern of the fluctuations. Fig. 3 shows the fluctuation spectrum of the cosmic ray ionizing component intensity inferred from the IZMIRAN scintillation supertelescope data (Bezrodnykh *et al.*, 1982). The displayed spectrum is typical of the steady-state interplanetary medium. Many spectral lines of minor amplitudes (none exceeding the 90% confidence level) can be seen at all frequencies from 1.6 x 10^{-3} up to 7 x 10^{-6} Hz. A similar analysis for approximately the same period (1979-1984) made in the

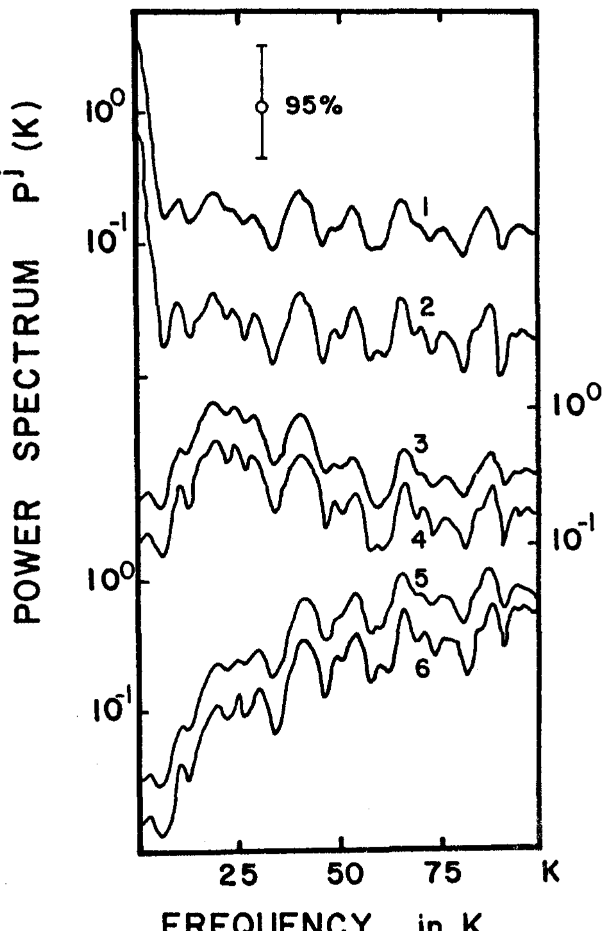


Fig. 3. The cosmic ray intensity fluctuation spectrum inferred from the IZMIRAN scintillation telescope data. Frequency in 1/60 000 Hz.

1.4 x 10^{-4} - 8 x 10^{-6} Hz band during different periods (Figs. 4 a-c) has revealed fluctuations with periods of about 160-, 200- and 420-min prior to interplanetary medium disturbances. In the latter case, the 160- and 200-min fluctuations are preserved, but exhibit smaller amplitudes. The enhancement of the 7-hour cosmic ray fluctuation and the simultaneous suppression of the 160-min fluctuation are probably con-

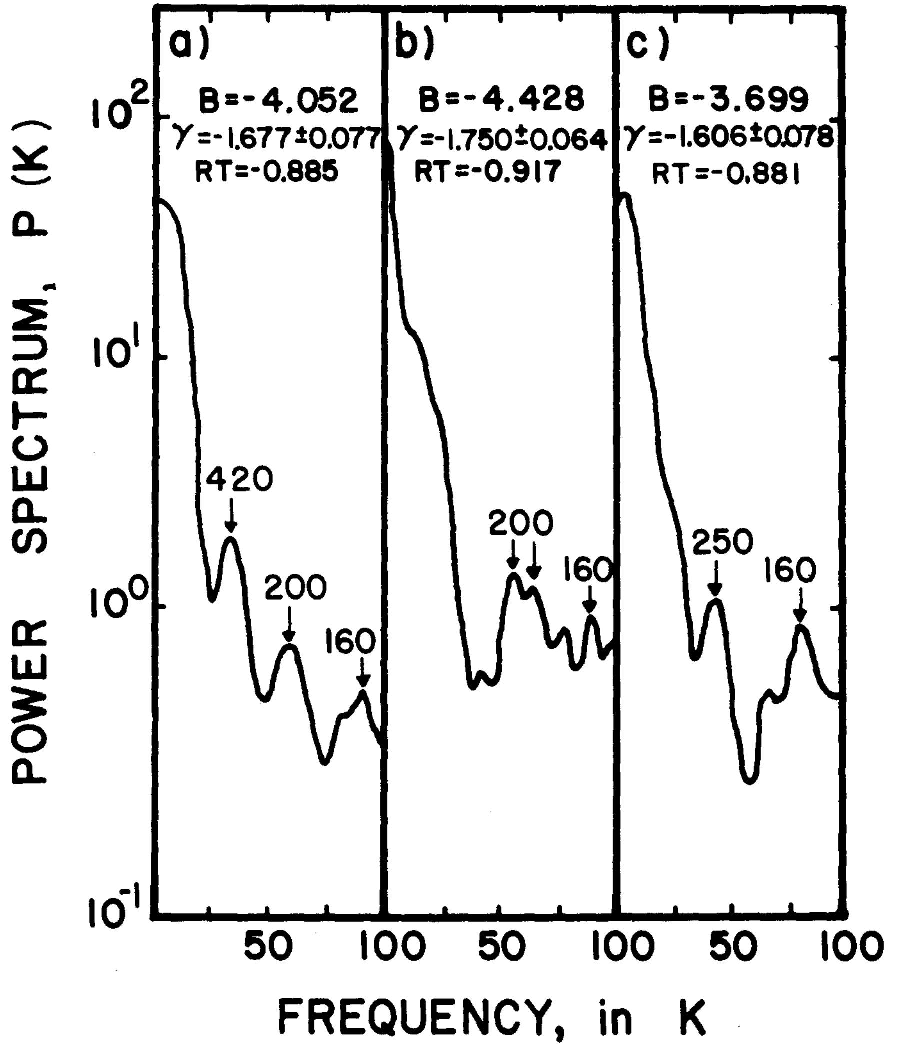


Fig. 4. The cosmic ray fluctuation power spectra for various events in 1979-1984. Frequency in 1/60 000 Hz.

tingent on the interplanetary magnetic field fluctuations in the interplanetary shock waves (Kozlov, 1981a) arriving at the Earth and on the processes of cosmic ray acceleration by such waves. This rearrangement is especially noticeable in the spectral characteristics of cosmic ray fluctuations in the 2×10^{-4} - 2×10^{-5} Hz band. Fig. 5 (a, b) presents the instantaneous spectra calculated using the Kerguelen data of September 20, 1977 obtained before the Forbush decreases. The figure shows lucidly the dynamics of the transition from a featureless spectrum (curves 1-3) to a spectrum with clear peaks (curves 6-8), in particular with the peak at 8×10^{-4} Hz which dissipated completely 24 hours before the Forbush decrease. It should be noted that the spectrum in the frequency band below 5×10^{-5} Hz got much steeper. The relevant calculations of the spectral indices in the frequency band $10^{-5} \leqslant f \leqslant 10^{-4}$ Hz have shown that the value of γ varies from -1.6 for curves 1 and 2 to -3.8 for curves 12 - 14, *i.e.* even a day before the September 22 Forbush decrease.

Unfortunately, the pattern in the low-frequency band is not always so unambiguous, namely, the rearrangement occurs practically in all cases, but differently in different periods. Fig. 6 shows the instantaneous spectra for the September 1977 Forbush decrease inferred from the Utrecht data. The spectral rearrangement at Utrecht began in practice two days before the commencement of the interplanetary medium disturbance in the Earth vicinity, almost simultaneously with that at Kerguelen. Nevertheless, the spectral indices varied within a much narrower interval (from 1.2 to 2.4); moreover, unlike the Kerguelen data, the statistically significant peak at Utrecht shifted explicitly to a lower-frequency band 18 hours before the Forbush decrease. Such an effect is often observed in the high-latitude monitor data (Kozlov, 1981b; Bezrodnykh *et al.*, 1982), but is comparatively rare in the midlatitude data.

Thus, the cosmic ray propagation in interplanetary space is accompanied by the characteristic cosmic ray fluctuations whose power spectra are rearranged prior to interplanetary medium disturbances throughout the entire frequency band (Dorman *et al.*, 1983; Blokh *et al.*, 1984; Bezrodnykh *et al.*, 1982). The rearrangement mechanisms are very different for different frequency bands (Dorman and Libin, 1985) and, therefore, it is of interest to study the feasible versions of the spectral rearrangement for the interplanetary medium disturbances of various kinds and to compare the resultant spectra with the same spectra calculated in terms of different models (Owens, 1974).

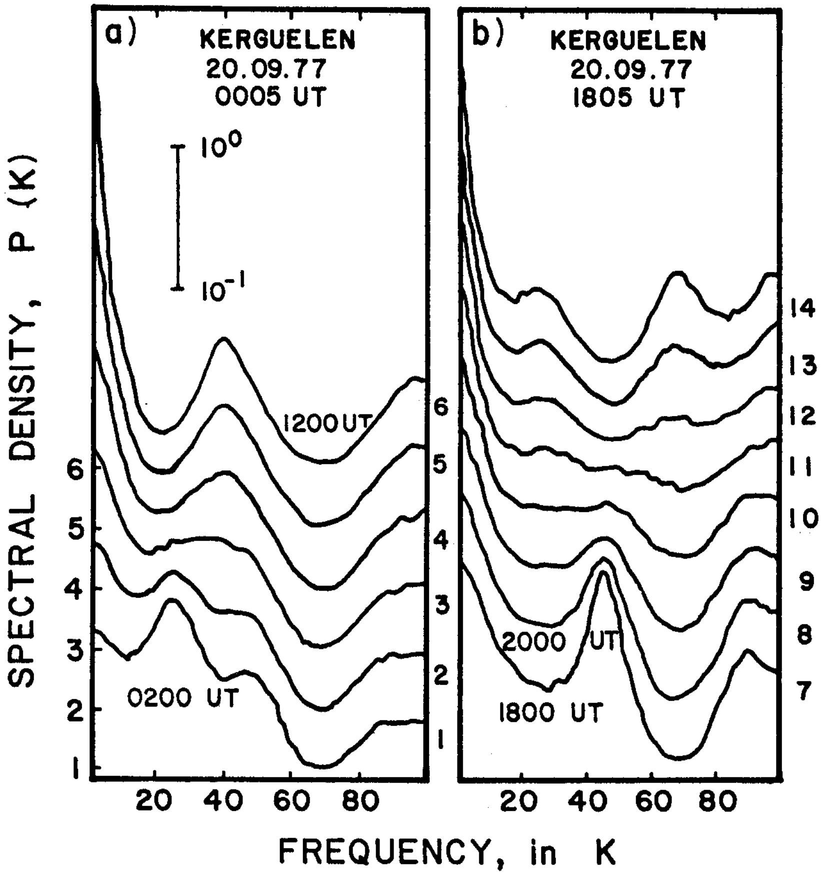


Fig. 5. Instantaneous spectra of cosmic ray intensity at Kerguelen on September 20, 1977. Frequency in 1/60 000 Hz.

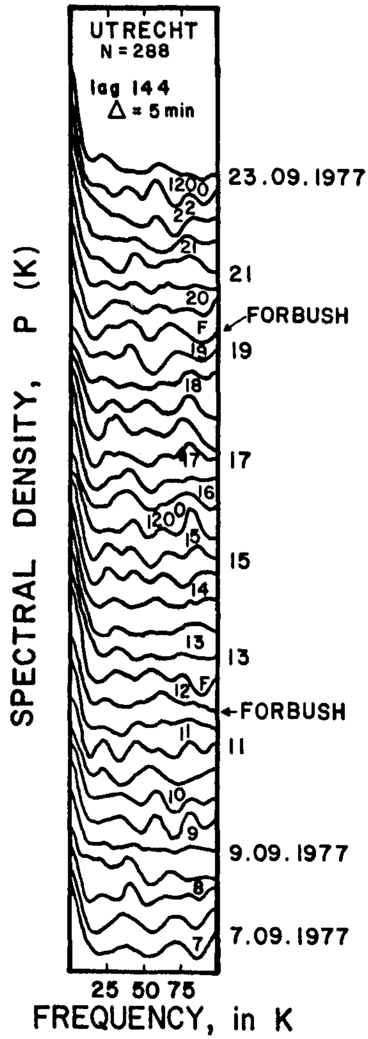


Fig. 6. Instantaneous spectra of cosmic ray intensity at Utrecht for the period September 7-23, 1977. Frequency in 1/60 000 Hz.

COSMIC RAY FLUCTUATIONS AND HIGH-SPEED SOLAR WIND STREAMS

When analyzing the spectra in the low-frequency band, it is interesting to examine the fluctuations associated with recurrent high-speed solar wind streams. The lifetime of a high-speed stream associated with a coronal hole may vary from less than one solar rotation (~27 days) to 10-20 or more revolutions. At the same time, a high-speed stream existing for such a long period is not something invariable. The sizes and positions of the coronal holes in the solar corona vary in time, so the recurrent high-speed streams and the cosmic ray fluctuations associated with them must evolve accordingly.

The high-speed streams at the Earth orbit can reach 3×10^{13} cm across, so a stream where the mean magnetic field intensity is ~5 nT can effectively affect high-energy particles of 5×10^{10} to 5×10^{11}eV. Thus, the high-speed stream effects must be clearly expressed at least in the neutron component.

In view of this, it is important to study the cosmic ray fluctuations inside high-speed streams. With this purpose we analyzed the data obtained in 1973-1974, *i.e.* during the years of solar activity decay, when numerous long-lived high-speed streams were observed. The behaviour of the large-scale cosmic ray fluctuations inside high-speed streams was examined using the cosmic ray neutron component data from Deep River. When plasma transverses a high-speed stream, the plasma velocity varies rapidly inside the stream. Near the stream borders, especially near the leading edge, the velocity is distorted due to the high-speed stream interaction with the steady-state solar wind. Therefore, the fluctuations were studied for days when the Earth was inside a high-speed stream. All such streams were classified into three groups according to the speed values, namely: Group I, which includes streams with speeds below 600 km/sec; Group II, streams with speeds between 600 and 700 km/sec; and Group III, streams with speeds above 700 km/sec. The values of the amplitudes, phases and spectral indices of the large-scale fluctuations were calculated for each individual group and for the entire sample.

The examination of the first two harmonics of the diurnal variation by the proposed method has shown that the amplitudes of the two harmonics inside high-speed streams is 20 - 25% higher than in the steady-state solar wind; the phase of the first harmonic within a high-speed stream shifts to earlier hours (by about one hour), while the phase of the second harmonic shifts to later hours (by about 1.3 hours).

The analysis of the entire sample agrees with the above results, namely, as the mean V_{max} value in the stream increases, the amplitudes of the first and second harmonics become larger, while their phases shift in the same manner as described above.

The higher-frequency fluctuations (7-hour, 3-hour, etc.) show the same behaviour depending on the solar wind stream velocity. Indeed, the homogeneity degree of the magnetic field within a high-speed stream depends on the plasma velocity in it, *i.e.* the flux field variability σ_B decreases as the speed increases. If σ_B is assumed to characterize the number of magnetic inhomogeneities in a high-speed solar wind stream, we shall arrive at the conclusion that the field regularization inside the stream enhances with increasing flux velocity.

Fig. 7 shows the variation modes of the solar wind velocity V_{max} in a recurrent high-speed stream and of the stream width Δt (in days), from May to October, 1973, when they were recorded during eight successive passages of the Earth through the stream. It is seen that V_{max} = 600 km/sec during the first passage through the stream. During the subsequent passages, the value of V_{max} increased rapidly and reached a maximum in the third revolution (~750 km/sec), whereupon the velocity decreased gradually to V_{max} ~575 km/sec at the end of the stream lifetime. The value of Δt shows a similar behaviour. Shown in Fig. 7b, c for the same recurrent stream is the behaviour of the r.m.s. deviation of the total vector modulus of the magnetic field in the stream σ_B, of the spectral index of the differential Forbush decrease energy spectrum γ_F, and of the spectral index of the cosmic ray fluctuation power spectrum in the 1.4×10^{-6} - 10^{-6} Hz frequency band. All these parameters can, to one degree or another, characterize the magnetic field irregularity extent in the stream. From Fig. 7b, c it follows that the variations of σ_B, γ_F, and γ_S are most evidently characterized by the decrease of their values from the first to third revolution and the subsequent increase from the sixth to eighth revolution, by the appearance of strong fluctuations in the middle of the stream life-time, and by the changes of the three parameters in antiphase with V_{max} and Δt. The value of the spectral index γ_S of the cosmic ray fluctuation power spectrum varies throughout the high-speed stream lifetime from $\gamma_S = 1.0$ to $\gamma_S = 1.9 \pm 0.2$. It is characteristic that, as V_{max} and Δt rise, the cosmic ray fluctuation spectrum gets more and more rigid due to the decay of the high-frequency side of the spectrum, thereby indicating substantial changes in the inhomogeneity spectrum of the magnetic field in the high-speed stream.

The results obtained have shown that the parameters of recurrent high-speed solar wind streams and the associated large-scale cosmic ray fluctuations do not vary randomly in time, but rather exhibit the clearly expressed regularities. Therefore, the duration of the streams and the dynamics of the fluctuation behaviour inside the proper streams must be allowed for when studying the recurrent high-speed solar wind streams.

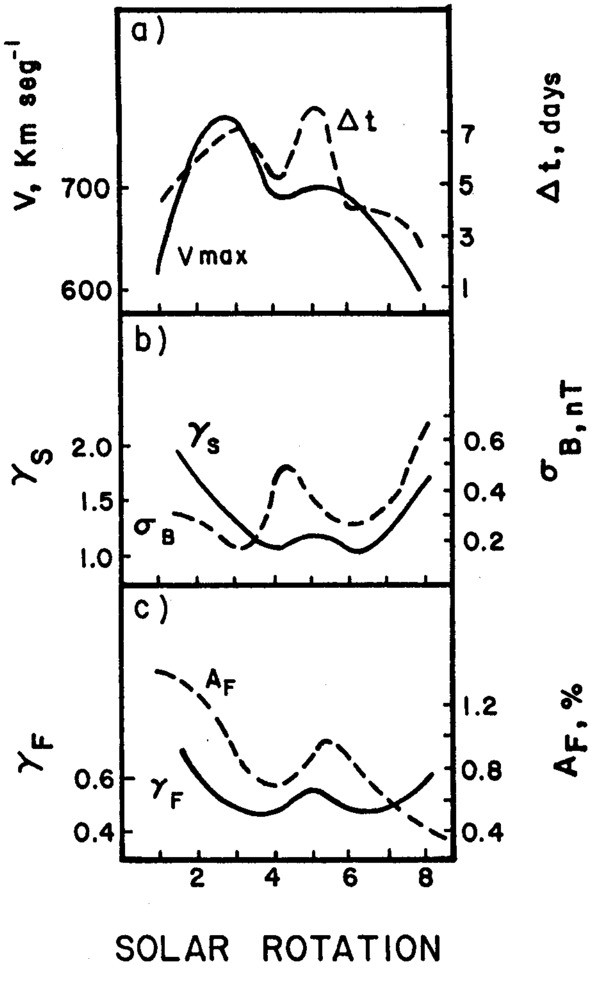


Fig. 7. Behaviour of: (a) the large-scale fluctuations of solar wind velocity (V_{max}) and the high-speed stream width (Δ t); (b) the r.m.s. deviation; and (c) the spectral indices γ_F and γ_S for periods in 1973-1974.

SPECTRAL CHANGES OF COSMIC RAY FLUCTUATIONS AND IMF SHOCK WAVES

The changes in the spectral estimates of the large-scale fluctuations occur as a rule 1 to 3 days before the arrival of an interplanetary medium disturbance at the Earth; this corresponds approximately to the time of propagation of a shock-wave from the Sun to the Earth orbit (Dorman and Libin, 1985). It seems natural, therefore, to make an attempt to account for the variations of the fluctuation spectra and for their dynamics by the changes in the flux of particles reflected from the front of the approaching shock wave. The magnetic field structure in front of the perturbation propagating in the interplanetary medium is considered to be invariable. If this hypothesis is correct, then the observed fluctuation power spectrum variations will arise from the rigidity increase in the spectrum of the anisotropy observed in steady solar wind with the reflection by a softer particle flux directed in practice oppositely. This assumption is in good agreement with the results of experimental calculations of cosmic ray fluctuations (see Fillisetti *et al.*, 1982; Dorman *et al.*, 1983; Blokh *et al.*, 1984; and previous sections of the present work). In Kozlov (1981 a, b) it can be seen that the fluctuations get enhanced in the high-frequency band $f \geqslant 10^{-4}$ Hz before disturbances, thereby reducing the spectral index in the power-law description of the $\sim f^{-\gamma}$ type from -1.5 - -2.0 to positive values of γ. In this case, as indicated above, the spectrum in the frequency band below 10^{-4} Hz behaves oppositely, namely, the value of γ varies from -1.2 to -3.8 (resembling the motions of butterfly wings with the center at frequencies of about 3×10^{-4} Hz). According to Owens (1974), the cosmic ray fluctuation power spectrum normalized to the squared mean intensity of the flux may be presented as

$$\frac{P_n(f)}{n_0^2} = \frac{P_B(f)}{B_0^2} \, C(f, \mu, R)\delta^2$$

where $P_B(f)$ is the interplanetary magnetic field spectrum; δ is the projection of cosmic ray anisotropy on the magnetic field direction; $C(f, \mu, R)$ is the resonance function whose plots (calculated at two rigidity values R_1 and R_2) are shown in Fig. 8a. In this figure curves 1 and 2 are for rigidities R_1 and R_2, and curve 3 is the shape of the resonance function averaged over energies. As the rigidity of the anisotropy spectrum enhances, the relative contribution of high-energy particles increases (curve 2), thereby making the spectrum slope steeper in the low-frequency band and flatter in the high-frequency band $f \geqslant 10^{-4}$ Hz due to the more substantial effect of the gently-sloping "tails" of the function at high rigidities and to the increased contribution of the Poisson noise to the spectral estimates. The anisotropic fraction of the reflected particle flux is distributed in the space before the shock wave front according to the law (Belov *et al.*, 1973; Shakhov and Dorman, 1974)

$$A(r,\theta,R) = \frac{\Lambda}{r} D(R) \Sigma \frac{A_n r_B}{x\ \sigma_n} \left(\frac{r}{r_B}\right)^{-\sigma_n} P_n(\cos\theta)$$

where Λ is the transport scattering path; r_B is the shock front radius; r is the distance to the front curvature center; θ is an angle measured from the screen center; D(R) is the screen transparence coefficient introduced by us and depending on particle rigidity; A_n and σ_n are defined by the expressions

$$A_n = \frac{2n+1}{2} \int_0^{\theta_0} \sin\theta\, P_n(\cos\theta)\, d\theta - \int_{\theta_0}^{\theta_1} x(\theta) \sin\theta\, P_n(\cos\theta)\, d\theta$$

$$\sigma_n = \frac{1}{2} + \left[\frac{1}{4} + n(n+1)\frac{x_\perp}{x_\parallel}\right]^{1/2}$$

Here $x_\perp$ and x are respectively the transverse and logitudinal diffusion coefficients; $X(\theta)$ is a decreasing function. Assuming that $D(R) \sim |x_{\parallel AP}|$ (where $x_{\parallel AP}$ is the longitudinal diffusion coefficient behind the shock front (Shakhov and Dorman, 1974)), we obtain that $D(R) \sim R^{\nu-4}$ if the IMF fluctuation power spectrum behind the shock front is $P(F) \sim B_0 f^{-\nu}$. The latter has properly been corroborated by the results of the IMF fluctuation studies and by the direct calculations of the IMF power spectra carried out by the authors.

The expected variations of the spectrum in case of spherical shock wave ($\theta = \Pi$) at an observation point located on the line of force running through the front center $\theta = 0$ were numerically calculated in view of studying the feasible interpretation of the rearrangement of the cosmic ray fluctuation power spectra on the Earth in the course of shock wave propagation in the interplanetary medium (Dorman *et al.*, 1986). The front velocity was assumed to be about 7×10^7 cm/sec, and the transverse-to-longitudinal diffusion coefficient ratio to be

$$x_\perp / x_\parallel \simeq R^{-2}$$

The choise of the latter parameter is sufficiently arbitrary, but its application does not substantially affect the qualitative pattern. The calculations were made using the neutron monitor coupling coefficient and assuming that the pitch-angle distribution cosine is about 0.5.

Figs. 8 b, c, d are the resonance function plots reflecting the variations of the cosmic ray fluctuation power spectrum in case of an invariable interplanetary magnetic field structure, and the calculated theoretical variations of the spectral index γ. The cases (b) - (d) differ in the reflected particle anisotropy value, namely, $A_{ref} = A_{quiet}$,

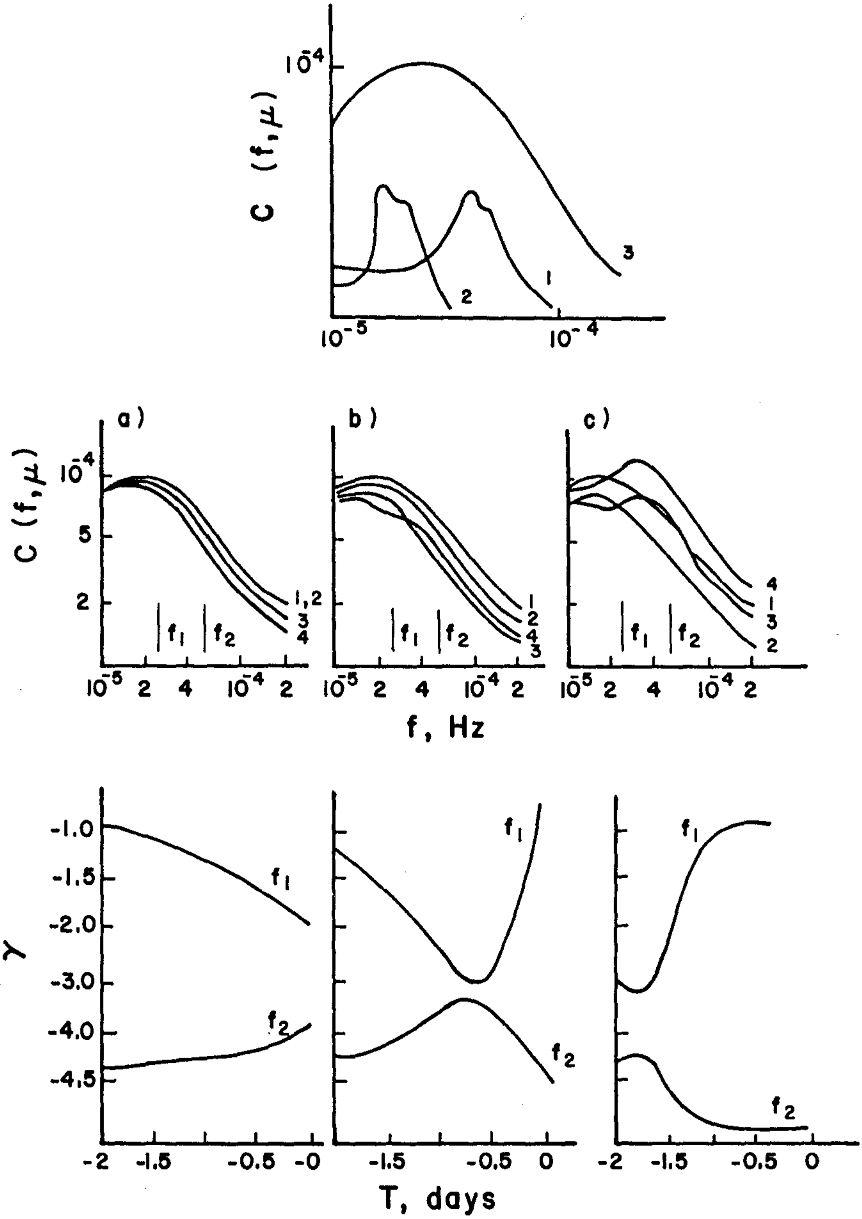


Fig. 8. The resonance function C (f, μ, t) calculated making allowance for the anisotropy value (refer to text for explanation).

$A_{ref} = 2\ A_{quiet}$, and $A_{ref} = 4\,A_{quiet}$ respectively. Curve 1 corresponds to the power spectrum during quiet periods; curves 2 and 3 are 24 and 12 hours before the shock wave arrival; curve 4 is immediately before the shock wave arrival at the Earth. In case of a small anisotropy, the cosmic ray fluctuation power spectrum increases gradually at frequencies below 5×10^{-5} Hz and decreases at frequencies above 10^{-4} Hz, in good agreement with about 70% of all the cases examined by the authors (Dorman and Libin, 1985). Moreover, the amplitude of the spectral index variations is also in good agreement with the experimental spectral slopes (Dorman and Libin, 1985). In the cases (c) and (d) the pattern is more complicated, namely, the amplitudes of the power spectra increase only in some of the frequency bands and the behaviour of the spectral indices is also more complicated. Nevertheless, the comparison of the results obtained with the experimental estimates of the behavioural dynamics of the spectra has demonstrated a good agreement in some 20 - 25% of the cases. Therefore, the difference in the behaviour of the spectra seems to be due in many respects to the different values of the anisotropy at the moment of spectral rearrangement.

Besides, when observed at different stations, the pattern will be shifted along the frequency axis to one direction or the other because of the different asymptotic directions of particle arrival corresponding to different pitch-angles.

SUMMARY

The calculated variations of the large-scale fluctuation spectrum shape have proved to be in good agreement with the spectral characteristics calculated experimentally on the basis of cosmic ray neutron and ionizing component data from Utrecht, Kerguelen, Moscow and Lomicky Stit. This leads us to conclude (from the character of the behaviour of the curves) that the anisotropy makes different contributions to the rearrangement of the cosmic ray spectra observed on the Earth.

Unambiguous conclusions are still difficult to come to; nevertheless, if a substantial particle flux with a soft spectrum is observed prior to shock wave arrival, the spectral rearrangement will be different at high and low anisotropy values. As a result, the instruments with different coupling coefficients will "see" different directions of the anisotropy vector, thereby giving rise to changes in the mutual phase spectrum before the shock wave arrival to the Earth. It should also be noted that the recurrent high-speed streams play an important role in calculating the cosmic ray

fluctuation power spectra. Can the events, which do not obey the regularities of the fluctuation behaviour dynamics found by Dorman and Libin (1985), Gulinsky *et al.* (1985), Blokh *et al.* (1984) and Dorman *et al.* (1983), arise from the passages of the Earth through the recurrent high-speed solar wind streams? This question will be answered only by systematic observations of the fluctuation events in cosmic rays on the basis of data from several instruments, if through during several years. Such observations are expedient to carry out in both low- and high-frequency bands. The mutual spectral analysis of cosmic ray intensity carried out using data of the cosmic ray general and neutron component measurements with the neutron monitor and the scintillation telescope at Moscow, has made it possible to expect that relationships will be found between the observed spectral shapes and the conditions in interplanetary space.

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