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SHAPE OF SPECTRUM OF GALACTIC COSMIC RAY INTENSITY FLUCTUATIONS

S.A. Starodubtsev
Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy, SB RAS,
Yakutsk, Russia, starodub@ikfia.ysn.ru

Abstract. The impact of solar wind plasma on fluxes of galactic cosmic rays (CR) penetrating from the outside into the heliosphere with energies above ~1 GeV leads to temporal variations in the CR intensity in a wide frequency range. Cosmic rays being charged particles, their modulation occurs mainly under impacts of the interplanetary magnetic field.

It is well known that the observed spectrum of interplanetary magnetic field (IMF) fluctuations in a wide frequency range ν from ~10^{-7} to ~10 Hz has a pronounced falling character and consists of three sections: energy, inertial, and dissipative. Each of them is described by the power law $P_{\mathrm{IMF}}(\nu)\sim\nu^{-\alpha}$, while the IMF spectrum index α increases with increasing frequency. The IMF fluctuations in each of these sections are also characterized by properties that depend on their nature.

Also known are established links between fluctuation spectra of the interplanetary magnetic field and galactic cosmic rays in the case of modulation of the latter by Alfvén or fast magnetosonic waves. The theory predicts that fluctuation spectra of cosmic rays should also be described by the power law $P_{\mathrm{CR}}(\nu)\sim\nu^{-\gamma}$. However, the results of many years of SHICRA SB RAS research into the nature and properties of cosmic ray intensity fluctuations based on data from neutron monitors at stations with different geomagnetic cut-offs R_C from 0.5 to 6.3 GV show that the observed spectrum of fluctuations in galactic cosmic ray intensity in the frequency range above 10^{-4} Hz becomes flat, i.e. it is similar to white noise. This fact needs to be realized and explained.

This paper reports the results of research into the shape of the spectrum of galactic cosmic ray intensity fluctuations within a frequency range ν from ~10^{-6} to ~1 Hz and compares them with model calculations of white noise spectra, using measurement data from the neutron monitor of the Apatity station. A possible physical explanation has been given for the observed shape of the cosmic ray fluctuation spectrum on the basis of the known mechanisms of their modulation in the heliosphere.

Keywords: neutron monitor, cosmic rays, interplanetary magnetic field, modulation, power spectrum, white noise.

INTRODUCTION

The diffusion flux of galactic cosmic rays (GCR) is known to constantly penetrate from the interstellar medium into the heliosphere. When propagating in the heliosphere, CRs are subject to a significant modulating effect of the solar wind (SW). As the Sun is approached, CRs assume a radial gradient, their intensity decreases, and depending on the level of solar activity there are significant temporal variations in its amplitude, which occur on large time scales — from minutes to eleven years and more. GCRs being charged and elementary particles (mainly protons) and nuclei of chemical elements up to iron, the main modulating factor of CRs is the interplanetary magnetic field (IMF).

Long-term satellite measurements of SW parameters show that depending on the level of solar activity not only large-scale IMF undergoes changes but its turbulent component as well. At the same time, its associated observable spectrum of IMF fluctuations occupies a fairly wide frequency range from 10^{-7} to 1 Hz and higher, and their power varies by at least 11 orders of magnitude from 10^{-4} to 10^{7} nT^2/Hz [Russell, 1972; Kovalenko, 1983]. In this case, the spectrum of IMF fluctuations has a falling character and is described by a power-law function $P_{\mathrm{IMF}}(\nu)=P_0\nu^{-\alpha}$, where $P_{\mathrm{IMF}}(\nu)$ is the power of IMF fluctuations at a frequency ν; P_0 is the spectrum constant; α is the exponent. The entire observable spectrum of IMF fluctuations can be divided into three sections in which its constituent oscillations and waves have different properties. These sections are called energetic, inertial, and dissipative. Their characteristic feature is the fact that at their boundaries, at frequencies of ~10^{-4} and ~0.1 Hz respectively, the spectrum sustains a fracture and becomes steeper with increasing frequency.

Since the spectrum of GCR intensity fluctuations with an energy of more than 1 GeV turns out to be linked with the IMF spectrum [Owens, 1974; Berezhko, Starodubtsev, 1988], its shape would seem to reflect the shape of the IMF fluctuation spectrum. However, numerous observations of the spectrum of CR intensity fluctuations from the worldwide neutron monitor network with different thresholds of geomagnetic cut-offs and different altitudes above sea level in different periods with respect to the state of the interplanetary medium and geomagnetic field show that this is far from the case. During quiet periods in the frequency range above ~10^{-4} Hz, the spectrum of CR intensity fluctuations is generally flat, which is characteristic of the white noise spectrum. This fact was first established in [Krymsky et al., 1973]. It requires understanding and explanation, which is the purpose of this paper.

1. DATA AND METHODS

The paper exploits measurement data on the field modulus from the WIND satellite with different sampling periods Δt=1 hr, 1 min, and 3 s, as well as from ACE with Δt=1 s. Measurements of the interplanetary medium parameters are freely available on the website [https://cdaweb.gsfc.nasa.gov/cdaweb/sp_phys for WIND and on [http://www.srl.caltech.edu/ACE/ASC] for ACE.

To identify GCR intensity fluctuation spectra, we have used data corrected for the barometric effect (sampling period of 1 day, 1 hr, and 1 min) from the neutron monitor 9-NM-64 of the CR station Oulu [https://cosmicrays.oulu.fi], as well as data (sampling period of 1 hr, 5 min and 1 min, 10 s and 1 s) from the neutron monitor 18-NM-64 of the station Apatity [http://pgia.ru/cosmicray].

While the distribution of CR particle rates per unit time is described by Poisson's law, we exploited the random number generator with Gaussian (normal) distribution for model calculations. This is due to the well-known fact that the Poisson distribution very quickly turns into the well-known Gauss distribution [Taylor, 1985]. When simulating the intensity of Gaussian noise, we used a FORTRAN subroutine, presented in [Otnes, Enokson, 1982], of the uniformly distributed random number generator, which makes it almost impossible to return to assigned condition. This important fact allows us to avoid theoretically possible pair and triple correlations of pseudorandom numbers. To control the operation of the Gaussian noise generator and quantify its characteristics (distribution density and statistics χ_0^2), programs based on the algorithms, also given in [Otnes, Enokson, 1982], have been designed.

The standard Blackman—Tukey method with a Tukey correlation window whose algorithm is also presented by Otnes, Enokson [1982] was used to calculate the power spectra of CR intensity fluctuations, IMF, and white noise. When constructing confidence intervals for estimating the power of fluctuations of different values, we took into account that the number of degrees of freedom *DoF* with the Tukey correlation window *DoF*=2.667n, where n is the cutoff coefficient of the covariance function [Jenkins, Watts, 1971].

2. RESULTS AND DISCUSSION

As an example, Figure 1 shows power spectra of GCR intensity fluctuations for August 2014 – February 2015. They were determined from measurements made by the neutron monitor of the station Oulu with different sampling periods Δt=1 day, 1 hr, and 1 min. There are well-known CR variations with periods of 27 days and 24 hrs in the spectra. Up to a frequency below 10^{-4} Hz, the spectra are falling and can be described by the power law $P_{CR}(\nu)\sim \nu^{-\gamma}$ with γ=2.326±0.001 and

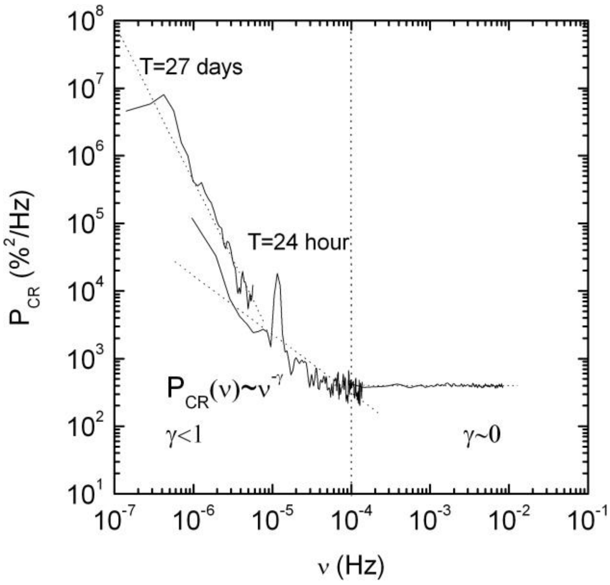

Figure 1. Spectra of GCR intensity fluctuations according to data from the Oulu station; 27-day and daily CR intensity variations. The vertical dotted line shows a conditional boundary between energy and inertial sections of the SW MHD turbulence spectrum. Straight dotted lines are least-squares fitting of spectra by the power law

γ=0.867±0.043 respectively. Nonetheless, at frequencies above 10^{-4} Hz, the spectrum abruptly changes its shape and becomes flat with γ =0.002±0.003. This is characteristic of white noise, and the shape of the CR fluctuation spectrum in this frequency range clearly differs from the known shape of the IMF fluctuation spectrum [Russell, 1972; Kovalenko, 1983].

Thus, the discrepancy in the shape of the spectra of GCR and IMF intensity fluctuations observed in numerous experiments requires its own understanding and explanation. Let us try to do this by analyzing the measurement data from the neutron monitor of the Apatity station and measurements of the IMF modulus from the ACE and WIND spacecraft on August 6–19, 2019, when the interplanetary medium and the geomagnetic field were quiet. Note that the data from the CR station Apatity has been retrieved only for the simple reason that it has a recording system providing information on CR intensity with different sampling periods Δt, up to 1 s and even shorter.

Figure 2 depicts the power spectrum of IMF modulus fluctuations observed at the same time. In this case, the spectrum is seen to be clearly incident, which can be described by the power law. As expected, with increasing frequency the spectrum of IMF fluctuations becomes steeper, while its index α for different regions varies from 1.28 to 1.67. On the other hand, Figure 3 illustrates the CR fluctuation spectrum as measured at the Apatity station. It, in the same manner as Figure 1, clearly shows the peak corresponding to the known GCR intensity variation with a period T=24 hrs; and at frequencies ν >10^{-4} Hz, the spectrum, as in Figure 1, becomes flat with $\gamma\approx0$.

It should be noted that since long data series are used for calculations of the spectra, Figures 1–3 omit

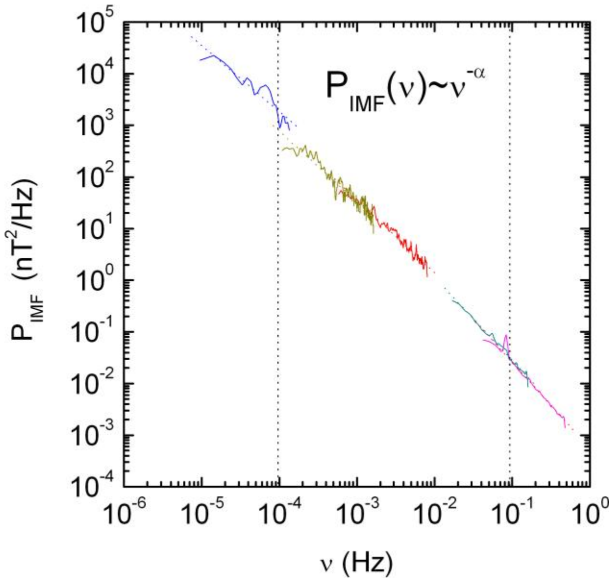

Figure 2. Spectrum of IMF modulus fluctuations from WIND and ACE measurements with different sampling periods (see the text). Designations are the same as in Figure 1

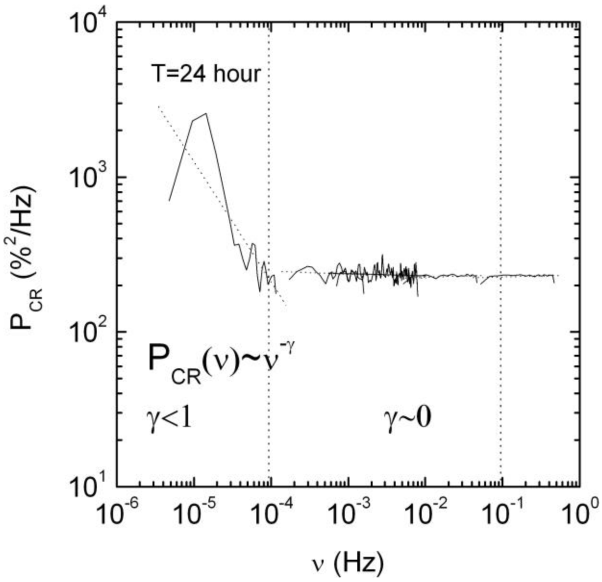

Figure 3. Spectrum of GCR intensity fluctuations according to data from the station Apatity. Designations are the same as in Figure 1

the confidence intervals because of their smallness.

Figure 4, *a–f* illustrates how the amplitude of GCR intensity fluctuations changes when recorded with different sampling periods Δt for August 6–19, 2019, as measured with the neutron monitor of the Apatity station. The amplitude was calculated here as the deviation of the count rate of the detector, attributed to its mean value over the entire period of interest. It can be seen that with decreasing Δt the amplitude of CR intensity variations increases significantly. A more detailed analysis of the data shows that with a decrease in Δt the amplitude increases from A≈0.5 %

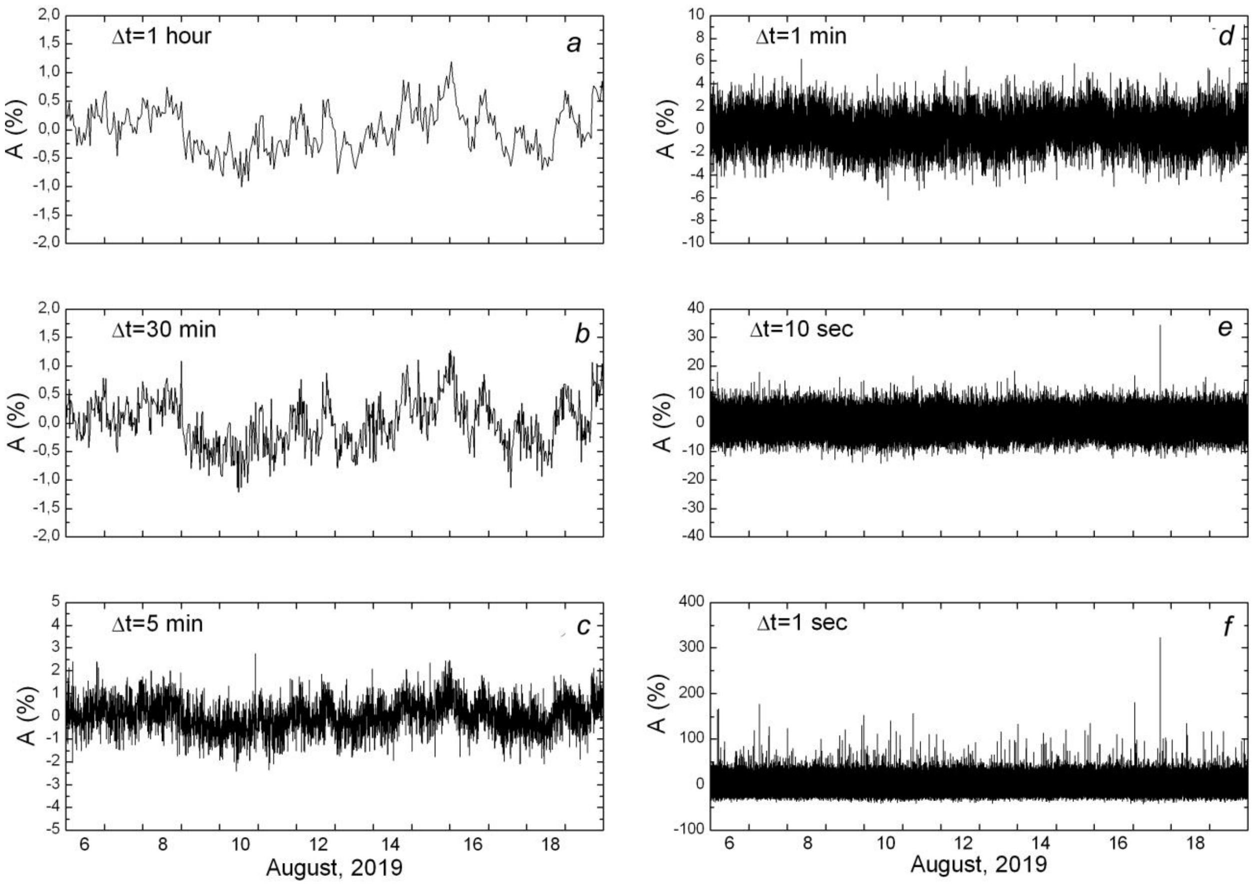

Figure 4. CR intensity with different sampling periods as a function of time for August 6–19, 2019, as measured by the neutron monitor of the Apatity station

(Figure 4, *a*, naked-eye CR intensity variation with T=24 hrs) to A≈50 % and higher (Figure 4, *f*); so, for example, for one-hour data the standard deviation is σ=0.44 %; for one-minute data, 1.44 %; and for one-second data, 10.76 %, i.e. with a decrease in Δ*t* during data gathering σ increases significantly.

Note that the directly observed CR variations at short Δ*t* are washed out by noise, and identifying their high-frequency part (the so-called CR fluctuations with T<2÷3 hrs), requires spectral analysis techniques (Figure 4, *d*–*f*). Attention is also drawn to single outliers in the form of a high-amplitude δ function when recording CRs with Δ*t* = 10 s and Δ*t* = 1 s (Figure 4, *d*, *f*). According to the developers of the neutron monitor data recording system from the Polar Geophysical Institute, the outliers are of physical origin and are caused by the arrival of ultrahigh-energy particles that produce multiple stars in the body of the monitor. Special studies of this phenomenon are being pursued [Balabin et al., 2011; Balabin et al., 2015].

To understand why the CR fluctuation spectrum at frequencies above 10^{-4} Hz is flat, the Gaussian noise corresponding to recording conditions has been simulated such that in the case of one-hour and one-minute data σ=1.41 %; one-second data, 11.07 %. As an example, Figure 5 shows a time series (N=20160 readings, which corresponds to an interval of 14 days; Δ*t*=1 min; σ=1.41 %) representing simulated noise with Gaussian distribution. This series fully corresponds to the GCR intensity characteristics for the period considered (see Figure 4, *d*). Figure 6 depicts its distribution density ρ with respect to σ and its approximation by the Gaussian function. To calculate ρ upon recommendations from [Taylor, 1985], we assumed that the number of bins N_{bin}=16 with ΔN_{bin}=0.5σ, with the number of degrees of freedom *DoF*=13.

In this case, the sum of distribution density values Σρ=0.9979 and normalized $\chi_0^2 = 0.3589$. The calculation results presented in Figure 6 and the statistics $\chi_0^2 < 1$ strongly suggest that the digital series generated obeys the Gaussian distribution.

The model series with Δ*t*=1 hr and Δ*t*=1 s were generated in the same way.

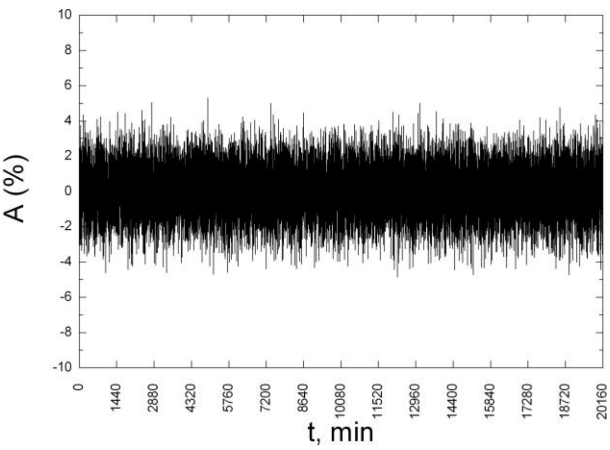

Figure 5. Time variations in the CR intensity for simulated noise with Gaussian distribution: N=20160, Δ*t*=1 min, σ=1.41 %

The power spectra of noise fluctuations corresponding to the model series are shown in Figure 7. In the frequency range spanning two orders of magnitude, the shape of the spectra is seen to match the shape of white noise, which can be described by the power function with γ≈0.

Comparison of Figures 3 and 7 shows that the experimental and model values of the power of CR intensity fluctuations and noise coincide well at frequencies above the critical frequency $\nu_{crit} \approx 10^{-4}$ Hz. Hence, the model satisfactorily describes the behavior of CR fluctuations at frequencies corresponding to T from 2–3 hrs to 2 s. At frequencies below the critical frequency, they differ significantly. A natural question arises — why?

The answer to it may be as follows. The cause of the flat (noise-like) CR fluctuation spectrum is the isotropization of the GCR flux that occurs during their propagation in the heliosphere due to scattering by MHD waves (Alfvén and magnetosonic) [Owens, 1974; Berezhko, Starodubtsev, 1988] and IMF static inhomogeneities frozen in SW. The entire observed spectrum of CR fluctuations

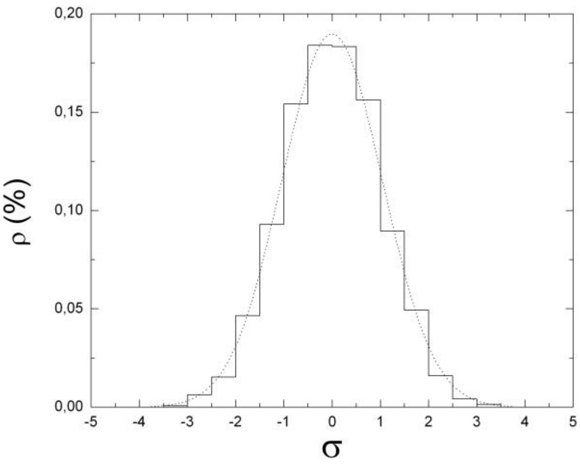

Figure 6. Distribution density ρ of the model noise, shown in Figure 5, relative to σ and its approximation by the Gaussian function

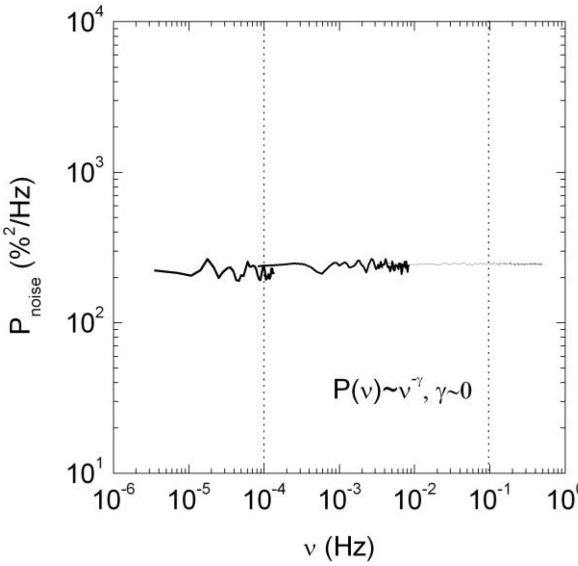

Figure 7. Gaussian noise fluctuation spectra calculated for model data with Δ*t* of 1 hr, 1 min, 1 s and standard deviations of 0.17, 1.41, and 11.07 % respectively

would seem to have this shape, yet it is well known that certain physical mechanisms of CR modulation are responsible for the mechanisms of occurrence of CR intensity variations of characteristic amplitude and frequency (or period). In particular, the convective diffusion mechanism is responsible for the diurnal CR variation [Krymsky, 1964]; and the mechanism of CR screening by sector IMF, for the semidiurnal one [Krymsky et al., 1981]. According to these theoretical works, when implementing such physical mechanisms the amplitude of the diurnal (T=24 hrs) CR variation $A\approx\approx 0.5$ %; that of the semidiurnal one (T= 12 hrs), ≈ 0.15 %. This is quite consistent with the mean values in long-term observations as well as with the mean power of the CR fluctuation spectrum $P(\nu)\approx 2\cdot 10^4$ %^{2}/Hz and $P(\nu)\approx 9.7\cdot 10^3$ %^{2}/Hz at respective frequencies $\nu\approx\approx 1.16\cdot 10^{-5}$ Hz and $\nu\approx 2.31\cdot 10^{-5}$ Hz. The occurrence of GCR fluctuations at the frequency $\nu_{crit}>10^{-4}$ Hz, which is the boundary between the energy and inertial regions of the MHD turbulence spectrum, is attributed to the CR modulation by fast magnetosonic waves. MHD waves of this type feature a large damping decrement and are generated locally in the vicinity of Earth by low-energy CR fluxes of solar or interplanetary origin [Berezhko, Starodubtsev, 1988].

Then not only the observed shape of the GCR intensity fluctuation spectra becomes clear, but also the dynamics of the CR intensity fluctuation spectrum observed before large-scale disturbances at frequencies $\nu_{crit}>10^{-4}$ Hz, on the basis of which a space weather forecasting method was developed at SHICRA SB RAS as far back as 1982 [Kozlov et al., 1984].

CONCLUSIONS

The analysis leads to the following conclusions.

1. The cause of the flat noise-like CR fluctuation spectrum at frequencies above the critical one $\nu_{crit}\approx 10^{-4}$ Hz is the isotropization of the GCR flux that occurs during their propagation in the heliosphere due to scattering by MHD waves of the Alfvén and magnetosonic type and IMF static inhomogeneities frozen in SW.

2. At frequencies below $\nu_{crit}\approx 10^{-4}$Hz, the incident spectrum of GCR fluctuations is observed. In this case, the spectrum is described by a power-law function $P(\nu)\sim\nu^{-\gamma}$ with $\gamma>1$.

3. At frequencies above ν_{crit}, a flat white noise-like spectrum is seen.

4. During large-scale SW disturbances at frequencies above $\nu_{crit}\approx 10^{-4}$ Hz, the amplitude (power) of CR fluctuations increases with the spectrum index becoming $\gamma<1$, and, accordingly, the spectrum of GCR fluctuations in the frequency range above 10^{-4} Hz changes its shape and becomes increasing.

5. The shape of the CR fluctuation spectrum in a wide frequency range differs significantly from the shape of the IMF fluctuation spectrum and is due to the implementation of the corresponding physical mechanisms of CR modulation in the heliosphere.

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