On the relationship of the temporal changes of the rigidity spectrum of the galactic cosmic ray intensity variations and power spectrum density of the interplanetary magnetic field turbulence

M.V. Alania , K. Iskra , M. Siluszyk

***Abstract*—The relationship of the rigidity spectrum of the galactic cosmic rays (GCR) intensity variations and the structure of the interplanetary magnetic field turbulence have been studied using data of neutron monitors and the components Bx, By, Bz of the interplanetary magnetic field (IMF) for four ascending and four descending epochs of solar activity (1967-2002). The exponent ν of the power spectral density of the IMF turbulence in the range of the frequencies 10^{-6} Hz – 10^{-5} Hz increases when the rigidity spectrum of the GCR intensity variations is hard and decreases when it is soft. Correlations between rigidity spectrum exponent γ, exponent ν and average amplitude of the power spectrum density (PSD) of the IMF turbulence in different periods of solar activity have been found. These features should be caused by the essential rearrangement of the structure of the IMF turbulence during the 11-year cycle of solar activity. The changes of the IMF turbulence can be considered as one of the important reasons of the 11-year variation of the GCR intensity for the energy >1GeV.**

1. Introduction

In papers [1]-[3] it was shown that about 75%-80% of the 11-year variation of GCR can be interpreted, based on the diffusion-convection model of GCR propagation; furthermore, it was shown that a general reason of the 11-year variation of the GCR intensity is a change of the character of diffusion of GCR particles versus solar activity [2]-[3]. According to the quasi linear theory [4], [6], the dependence of diffusion coefficient χ on the GCR particle's rigidity R should be defined by the structure of the IMF turbulence, as $\chi \propto R^{\alpha}$, where $\alpha \approx 2-\nu$, and ν is an exponent of the PSD of the IMF turbulence ($PSD \propto f^{-\nu}$, f is frequency); this dependence is significant among equally important dependencies of the diffusion coefficient on the other parameters of the solar activity and solar wind [4]-[7].

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In addition, it was shown that:
1) the temporal changes of the diffusion coefficient of the GCR particles are related with the change of the PSD in the frequency range of 10^{-6} Hz – 10^{-5} Hz of the IMF turbulence versus solar activity [2]-[3], [8],
2) the exponent γ of the rigidity R spectrum $\delta D(R)/D(R)$ ($\delta D(R)/D(R) \propto R^{-\gamma}$) of the GCR intensity variations (for the diffusion-convection approximation) generally is determined by the parameter α, ($\gamma \approx \alpha$), which shows the dependence of the diffusion coefficient χ on the rigidity R of the GCR particles ($\chi \propto R^{\alpha}$) [9]-[11].

The existence of the relationship $\nu \approx 2-\gamma$ between the exponent γ and the exponent ν was shown based on the neutron monitors experimental data and modeling of the Parker's transport equation [8], [10]; in general, the relationship between γ and ν is valid not only for the long-period variations but for the Forbush effects of GCR intensity [12], [13]. It is seen from the expression $\nu \approx 2-\gamma$, that the decrease of the exponent γ of the rigidity spectrum of the GCR intensity variations is observed owing to the increase of the exponent ν of the PSD in the energy range of the IMF turbulence ~10^{-6} Hz –10^{-5} Hz. So, the temporal changes of the rigidity spectrum exponent γ of the GCR intensity can be considered as a vital index to study the 11-year variations of the GCR intensity and to estimate the exponent ν of the PSD in the energy range of the IMF turbulence ~10^{-6} Hz – 10^{-5} Hz, as well. Thus, the rigidity spectrum exponent γ of the GCR intensity variations remains as a very important index in the cases, when the direct (in situ) measurements of the IMF are absent. Owing to the dependence of the exponent ν on the frequency of the IMF turbulence f [14], according to the the relationship γ ≈ 2 – ν, there should be exist a reliance of the exponent γ on the rigidity R of the GCR particles, i.e. there should be existed the dependence of the exponent γ on the frequency f of the IMF turbulence. Namely, when the frequency f decreases (or a rigidity R of GCR particles increases) the exponent γ increases [11].

2. EXPERIMENTAL DATA, METHODS AND DISCUSSION

We use the thoroughly selected monthly average data of neutron monitors for four ascending and four descending phases of solar activity for the A>0 and the A<0 epochs (1960-2002). A criterion for the data selection was continuously function of neutron monitors with different cut off rigidities throughout the period to be analyzed. The magnitudes J_i^k of the monthly average variations of the GCR intensity for 'i' neutron monitor were calculated, as: $J_i^k = \frac{N_k - N_0}{N_0}$; N_k is the running monthly average count rate (k =1,2,3,….months) and N_0 is the monthly average count rate for the year of the maximum intensity (in the minimum epoch of solar activity). The count rate of the maximum intensity is accepted as the 100% level; the year of maximum intensity is called a reference point (RP). The magnitudes J_i^k of the monthly average variations of the GCR intensity measured by 'i' neutron monitor with the geomagnetic cut off rigidity R_i and the average atmospheric depth h_i are defined as [15]:

$$J_i^k = \int_{R_i}^{R_{max}} \left(\frac{\delta D(R)}{D(R)} \right)_k W_i(R, h_i) dR \, , \qquad (1)$$

where $(\delta D(R)/D(R))_k$ is the rigidity spectrum of the GCR intensity variations for the k month; $W_i(R,h_i)$ is the coupling coefficient for the neutron component of GCR [14], [15] and R_{max} is the upper limiting rigidity beyond which the magnitude of the GCR intensity variation is vanished. For the power law rigidity spectrum $\left(\delta D(R)/D(R) \right)_k = AR^{\gamma_k}$ one can write:

$$J_i^k = A_i^k \int_{R_i}^{R_{max}} R^{-\gamma_k} \, W_i(R, h_i) \, dR \qquad (2)$$

where J_i^k is the observed magnitude at given month k and A_i^k is the magnitude of the GCR intensity variations recalculated to the heliosphere.

The values of the A_i^k are the same (in the scope of the accuracy of the calculations) for any 'i' neutron monitor when the pairs of the parameters γ_k and R_{max} are properly determined.

A similarity of the values of the A_i^k for various neutron monitors is an essential argument to affirm that the data of the particular neutron monitor and the method of the calculations of γ_k are reliable. To find the temporal changes of the energy spectrum exponent γ_k (k =1, 2, 3 ... months) a minimization of the expression $\phi = \sum_i^n (A_i^k - A^k)^2$ (where $A^k = \frac{1}{n}\sum_i^n A_i^k$ and n is the number of neutron monitors) has been provided [8]–[10]. The values of the expression $\int_{R_i}^{R_{max}} R^{-\gamma_k} \, W_i(R, h_i) \, dR$ for the magnitudes of R_{max} (from 30 GV up to 200 GV with the step of 10 GV) and γ (from 0 to 2 with the step of 0.05) were found based on the method presented in [13], [16].

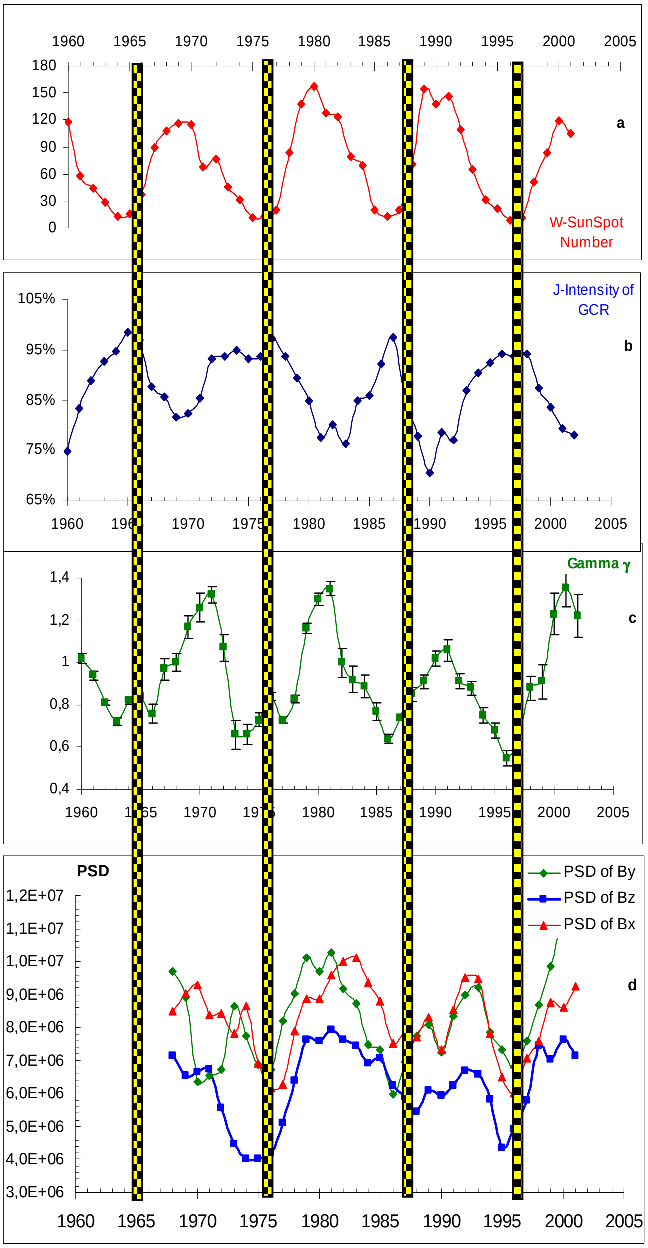

Figure 1abcd. The temporal changes of the smoothed semi annual average magnitudes for the whole period of investigation (1960-2002):

a) The sunspot numbers W

b) The GCR intensity J measured by Climax neutron monitor

c) The rigidity spectrum exponent γ

d) The average value of PSD for the Bx, By and Bz components of the IMF turbulence

The upper limiting rigidity R_{max}, beyond which the magnitude of the GCR intensity variation is vanished, equals 100 GV. This assumption is a reasonable for the 11–year variation of the GCR intensity [18]. A minimization of the expression ϕ for the smoothed monthly means (with the interval of 13 months) of the magnitudes of the 11–year variation of the GCR intensity has been provided with respect γ_k for given number of neutron monitors and the temporal changes of the rigidity spectrum exponent γ_k for all eight periods using the expression (2). The changes of the smoothed semi annual average magnitudes J_i^k of the GCR intensity variations of Climax neutron monitor data normalized with respect maximum intensity of 1965, the rigidity spectrum exponent γ_k, the sunspot number and the average value of PSD for the Bx, By and Bz components of the IMF turbulence are presented in Figure 1abcd for the whole period of investigation (1960-2002). Figure 1abcd shows that a distinction between the temporal changes of the rigidity spectrum exponent γ_k for the A>0 and the A<0 polarity epochs is not recognizable; we can see a good anti correlation between J_i^k and the sunspot numbers W and the rigidity spectrum exponent γ, and good correlation between γ and W (see Table).

TABLE

Years	1960-1964	1966-1970	1971-1975	1977-1981	1982-1985	1988-1991	1992-1996	1998-2002	1960-2002
W & J	-0,97 ±0,08	-0,94 ±0,14	-0,69 ±0,24	-0,88 ±0,16	-0,94 ±0,11	-0,93 ±0,12	-0,99 ±0,05	-0,96 ±0,09	-0,83 ±0,20
J & γ	-0,71 ±0,24	-0,90 ±0,15	-0,75 ±0,23	-0,92 ±0,13	-0,96 ±0,09	-0,93 ±0,12	-0,92 ±0,13	-0,98 ±0,06	-0,65 ±0,24
W & γ	0,84 ±0,18	0,77 ±0,22	0,82 ±0,20	0,97 ±0,07	0,90 ±0,14	0,75 ±0,23	0,93 ±0,13	0,91 ±0,14	0,81 ±0,20

To show a relationship between γ and ν, and average PSD the yearly average values of the γ, ν, and average PSD for the B_x, B_y, B_z components of the IMF turbulence (in the frequency range of ~ (10^{-6} Hz – 10^{-5} Hz) were considered. The exponent ν and average PSD were found using the IMF experimental data [10] for the period of 1967–2002. To increase the statistical accuracy the smoothed yearly means (running interval of 3 years) of the rigidity spectrum exponent γ, the exponent ν, and average PSD for the Bx, By and Bz components of the IMF have been used; results of the calculations are presented in fig.2abc-4abc.

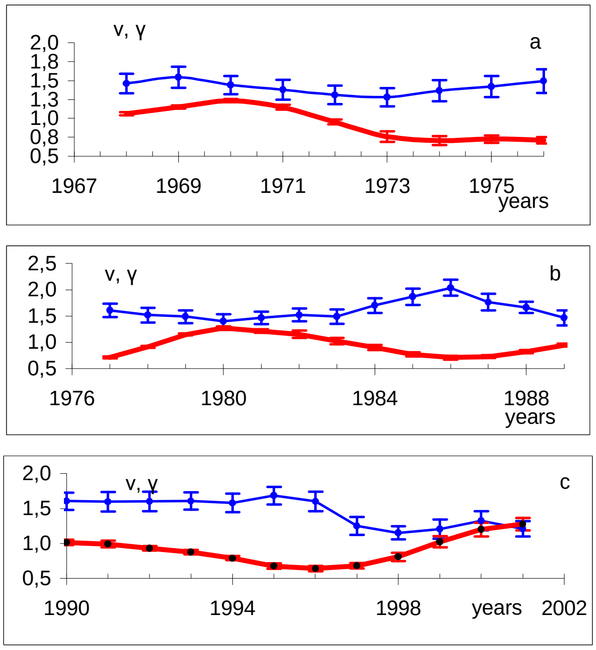

Figure 2abc The smoothed yearly values of the rigidity spectrum exponent γ (red-down) of the GCR intensity variations and the exponent ν of the PSD (blue-up) for the **By** component of the IMF turbulence for the period of 1967-1976 (a), 1977-1989 (b) and 1990-2001 (c).

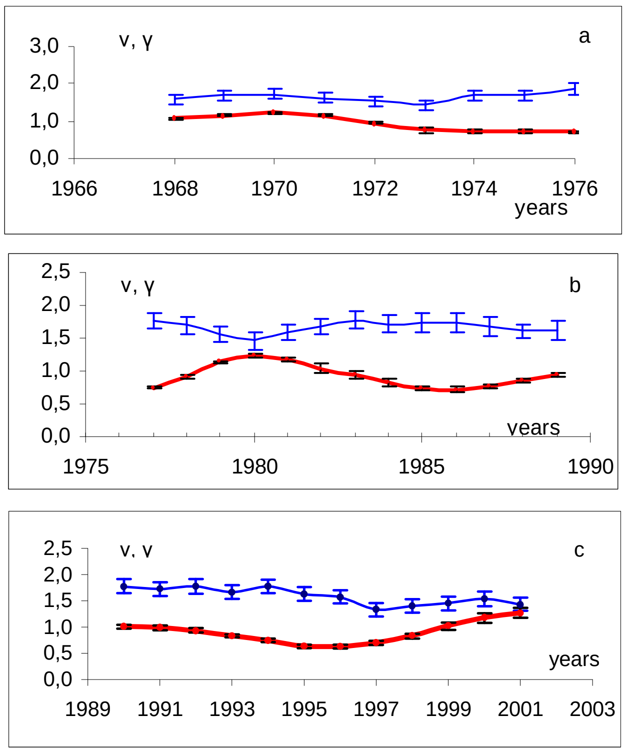

Figure 3abc The smoothed yearly values of the rigidity spectrum exponent γ (red-down) of the GCR intensity variations and of the exponent ν of the PSD (blue-up) for the **Bx** component of the IMF turbulence for the period of 1967-1976 (a), 1977-1989 (b) and 1990-2001 (c)

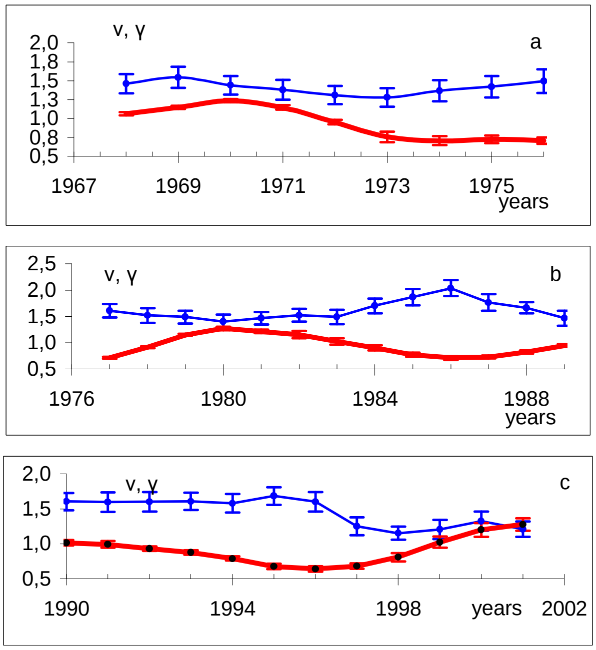

Figure 4abc The smoothed yearly values of the rigidity spectrum exponent γ (red-down) of the GCR intensity variations and of the exponent ν of the PSD (blue-up) for the **Bz** component of the IMF turbulence for the period of 1967-1976 (a), 1977-1989 (b) and 1990-2001 (c)

Turbulence of the By and Bz components of the IMF (perpendicular to the radial direction) insert a crucial contribution to the scattering of GCR particles in the heliosphere, although their roles are not equal at all. The power of the By component is significantly greater than the power of the Bz component.

According to the observed character of the relationship between γ and ν the considered period 1967–2002 could be divided into three different intervals, 1967-1976, 1976–1989 and 1990–2002. The changes of the smoothed average PSD for the Bx, By, Bz components of the IMF turbulence and γ are presented in fig.5a for the period of 1967–1976, for the period of 1976–1989 in fig.5b, and for the period of 1990–2002 - in fig.5c. Figures 5abc show that there are not noticeable correlations between the changes of γ and any PSD of the components Bx, By, and Bz for period 1966-1976 (a), while there are observed significant correlations among all above mentioned parameters for next two periods of 1977-1989 (b) and 1990-2001 (c)

We assume that either there is some global changes in the heliosphere during the periods of 1967 - 1976 and 1991 - 2001 / or ordinary Gaussian distributions of the IMF components alter into more complicated distributions, among them, e.g. as the lognormal distribution with the intermittence [16]; in this case the power spectrum is not sufficient to completely characterize the IMF turbulence.

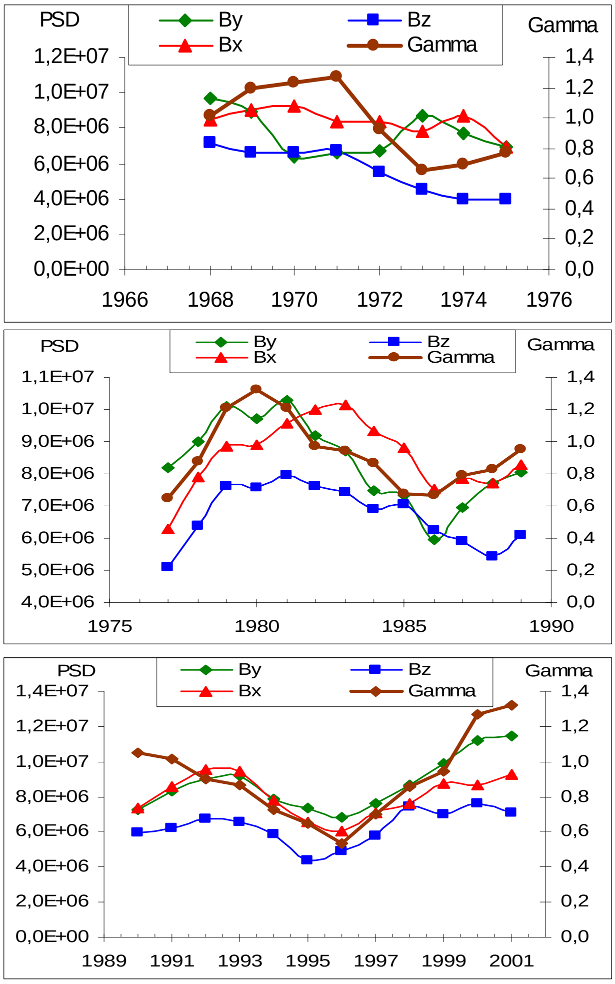

Figure 5abc The smoothed yearly average value of the PSD of the Bx, By and Bz components of the IMF turbulence and γ for the period of 1967-1976 (a), 1977-1989 (b) and 1990-2002 (c)

Generally high correlation between γ and ν demonstrates that the IMF turbulence is quite isotropy (for example in 1977–1989); indeed, besides, in situ data of the IMF confined by the local changes of the IMF, ν correlates well with the rigidity spectrum exponent γ of the GCR intensity variations reflecting the integral property of the large vicinity of the space. So, we do not exclude that the IMF turbulence becomes more anisotropic since 1990 up to 2000 (at least in the regions where in situ measurements have been carried out) and in situ local measurements of the IMF could not correspond to the changes in the large vicinity of space where the observed variation of GCR intensity takes place.

The relationship, $\gamma \approx 2 - \nu$ found in [10] gives a possibility to prove that the 11–year temporal changes of the rigidity spectrum exponent γ of the GCR intensity variations is related with the changes of the exponent ν of the PSD of the IMF turbulence versus solar activity. Thus, the strong inverse relationship is established between the temporal changes of the rigidity spectrum exponent γ and the GCR intensity (Fig.1bc).

This obvious relationship gives a possibility to estimate the roles of the changes of the regular and turbulence parts of the IMF in the long period variations (11 and 22 years) of the GCR intensity. We consider the temporal changes of the rigidity spectrum exponent γ as an important index responsible for the changes of 11–year variation of GCR intensity owing to the temporal changes of the IMF turbulence versus the solar activity.

3. CONCLUSION

1. We show that the soft rigidity spectrum ($\gamma \approx 1.2$-1.4) of the GCR intensity variations for the maximum epoch and the hard spectrum ($\gamma \approx 0.6$-0.7) for the minimum epoch of solar activity [8]-[10], [12] is the universal feature based on the calculations of neutron monitors data. This phenomenon is observed owing to the essential rearrangement of the structure in the range (10^{-6} Hz – 10^{-5} Hz) of the IMF turbulence throughout the 11-year cycle of solar activity. This region of the IMF turbulence is responsible for the scattering of the GCR particles with the energy of 5 GeV - 50 GeV to which neutron monitors respond.
2. We show that the average value of PSD of the Bx, By and Bz component for the maximum epochs is ~1.5 times greater than for the minimum epochs of solar activity in the ~10^{-6} Hz –10^{-5} Hz range of turbulence.
3. We demonstrate that the average values of the PSD of the Bx, By and Bz component are in good correlation with rigidity spectrum exponent γ of the GCR intensity variations for the periods of 1977-1989,and 1990-2002, while a correlation absents for the period of 1967-1976.
4. The rigidity spectrum exponent γ of the long period variations of the GCR intensity variations should be considered as a new (vital) index to study the 11-year variations of GCR intensity. Also, this index can be successfully used for the estimation of the state of the IMF turbulence in the range of frequencies ~10^{-6} Hz – 10^{-5} Hz. Therefore, data of GCR intensity variations are unique in the case of the IMF data absence. The exponent γ of the GCR intensity variations, and corresponding ν of the PSD of the IMF turbulence, can be found for the short arbitrary time interval determined by the accuracy of the GCR intensity data good enough for the calculation of the rigidity spectrum exponent γ.

REFERENCES

[1] Dorman, L I. “Cosmic ray long-term variation: even-odd cycle effect, role of drifts, and the onset of cycle 23”, *Adv. Space Res*., 27, No. 3, 601-606, 2001

[2] Alania, M.V., R.G., Aslamazashvili, T.B., Bochorishvili, K., Iskra, M., Siluszyk, The Role of drift on the diurnal anisotropy and on temporal changes in the energy spectra of the 11-year variation for galactic cosmic rays, Adv. Space Res. 27, 3, 613-618, 2001

[3] Alania, M.V., Stochastic variations of galactic cosmic rays, Acta Phys. Polonica B, 33, 4, 1149-1166, 2002

[4] Jokipii, J.R., Propagation of cosmic rays in the solar wind, Rev. of Geophysics and Space Physics, 9, 27-87, 1971

[5] Toptygin, I. N. Cosmic rays in interplanetary magnetic fields, D. Redel Publishing Company, Dordrecht, 1985

[6] Bieber, J.W., W. H., Mathaeus, C. W., Smith, et al., Proton and electron mean free paths: the Palmer consensus revisited, Astrophys. J., 420, 294-306, 1994

[7] Melnikov, Y.P., General correlation scales of random component of IMF, Geomagnetism and Aeoronomia , vol 45, 4 p. 445-452, 2005

[8] Siluszyk M., Iskra K., Modzelewska R. and Alania M.V., Features of the 11-year variation of galactic cosmic rays in different periods of solar magnetic cycles Adv. Space Res 35, 4, 677 2005

[9] Alania, M.V., K., Iskra, Features of the Solar Wind Large-Scale Structure in the Different Periods of Solar Activity Based on the Variations of Cosmic Rays, Adv. Space Res., 16(9), 241-244, 1995.

[10] Alania, M.V., K., Iskra, M., Siluszyk, Experimental and theoretical investigations of the 11-year variation of galactic cosmic rays, Adv. Space Res., 32, 4, 651-656, 2003

[11] Fisk, L.A., Goldstein, M.L., Klimas, A.J., et al., The Fokker-Planck Coefficient for Pitch-Angle Scatering of Cosmic Rays, *Astrophys. J.*, 190, 417-428, 1974

[12] Alania, M.V., K., Iskra, R., Modzelewska, M., Siluszyk, On the relationship of the energy spectrum indexes of the 11-year variation of galactic cosmic rays and the interplanetary magnetic field strength fluctuations, Proceedings of 28th ICRC, Japan, 3881-3886, 2003

[13] Wawrzynczak, A., Alania, M.V., "Peculiarities of galactic cosmic ray Forbush effects during October-November 2003" , Advanced in Space Research, 35, 682-686, 2005

[14] Jokipii, Coleman Cosmic ray diffusion tensor and its variations observed with Mariner 4. JGR 73, 5495, 1968

[15] Dorman, L I. Variations of galactic cosmic rays, Moscow,p.214, in Russian 1975

[16] Yasue, S., et al., Coupling coefficients of Cosmic Rays daily variations for neutron monitors, 7, Nagoya, 1982

[17] Burlaga, L. F., Lognormal and multifractal distributions of the heliospheric magnetic field, JGR., 106, A8, 15917-15928, 2001

[18] Lockwood J. A. and W. R. Webber, Comparison of the rigidity dependence of the 11-year cosmic ray variation at the earth in two solar cycles of opposite magnetic polarity, J. Geophys. Res., 101, A10, 21573-21580, 1996