ON THE NEW INDEX OF THE LONG-PERIOD MODULATION OF THE GALACTIC COSMIC RAYS INTENSITY*

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Data of neutron monitors have been used to calculate the temporal changes of the power law rigidity spectrum of the long period variations of the galactic cosmic ray (GCR) intensity for two positive ($A > 0$) and two negative ($A < 0$) polarity epochs of solar magnetic cycles (1960–2002). A relationship between the temporal changes of the rigidity spectrum of the long period variations of the GCR intensity and the power spectral density (PSD) of the interplanetary magnetic field (IMF) turbulence has been found. The soft rigidity spectrum of the long period variations of the GCR intensity for the maximum epochs and the hard spectrum for the minimum epochs should be caused by different structure of the IMF turbulence in the range of the frequencies 10^{-6}–10^{-5} Hz during the 11-year cycle of solar activity. A noticeable distinction between the temporal changes of the rigidity spectrum for the $A > 0$ and the $A < 0$ polarity epoch is not found. The temporal changes of the exponent of the rigidity spectrum of the long period variations of the GCR intensity should be considered as one of the important (new) indexes to study the 11-year variations of GCR intensity. The new index can be used to determine an exponent of PSD in the energy range 10^{-6}–10^{-5} Hz of the IMF turbulence. That region of the IMF turbulence is responsible for the scattering of the GCR particles of 5–50 GV rigidity to which neutron monitors are sensitive.

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1. Introduction and motivation

Solar activity in general is characterized by numbers of sunspots on the surface, changing from year to year. The increase and drop of sunspot numbers (variations in time) is called a cycle. There are observed quasi periodic changes, among which very powerful one is the periodicities of 9–13 years. These changes are called the 11-year solar cycle, as far the average periodicity is approximately equal to 11-years. Near sunspot minima epoch (few sunspots appear or they are not visible at all) the Sun is notably quiet with respect to the maxima epoch. So, each 11-year solar activity (sunspot cycle) lasts from one minimum to another minimum epochs. At the maximum epochs (roughly) of each 11-year sunspot cycle, the polarity of the Sun's global (approximately dipole type) magnetic field reverses so that the north magnetic pole becomes the south and vice versa. Every 22 years the magnetic polarity of the Sun is returning to its earlier state. So, there exists the 22-year solar magnetic cycle with two halves of 11 years period; each 11-year half of the 22-year solar magnetic cycle lasts from one maximum to another maximum epoch. When the global magnetic field lines are directed outward from the north hemisphere of the Sun and are directed backward to south hemisphere, this 11 year period is called the positive ($A > 0$) magnetic polarity period, while in vice versa case, it is called the negative ($A < 0$) magnetic polarity period of the Sun [1]. An existence of solar wind is the outstanding phenomenon for the Sun. The solar wind is an extension of the outer atmosphere of the Sun (the corona) into interplanetary space. The structure of corona is imposed by the solar magnetic field which extends from the solar surface out into the corona. Containing roughly equal number of electrons and protons the corona is an excellent electrical conductor. As a result of this super conductivity, the coronal plasma can move along but not across magnetic field lines. The solar magnetic fields embedded in the solar wind plasma ('frozen in') are carried into space by the solar wind to form the IMF. Because of solar rotation, the point where the open magnetic field line is anchored to the Sun moves and as a result the IMF has the form of a spiral [2]. At the orbit of the Earth, one astronomical unit (AU), the average speed of the solar wind is about 400 km/s and the IMF makes an angle of about 45 degrees to the sun-earth radial direction. This angle increases up to about 90 degrees to the radial direction and the IMF becomes nearly transverse. On the background of the relatively regular spiral IMF the large amplitude waves (Alfen and sound) as well as turbulence of large spectrum $\sim 10^{-6}$–10^{-5} Hz have been observed in the interplanetary space. Generally a stochastic part of the IMF magnetic field can be considered as a Gaussian distribution, so that the power spectrum should be sufficient to completely characterize the turbulence.

The vicinity of the space around the Sun, where solar wind with the IMF dominate, is called the heliosphere. The modern measurements by space crafts (Voyager 1 and Voyager 2) [3] show that the heliosphere is extended up to about 100 AU, continuously change the size and shape. The stochastic (turbulence) IMF is characterized by the large interval of frequency, ($\sim 10^{-7}$–10^{-1} Hz) and consists, in general, of energy, inertial and dissipation ranges. The frequency range of ($\sim 10^{-6}$–10^{-5} Hz) of the IMF turbulence is responsible for the scattering of GCR of the energy 5–50 GeV to which neutron monitors on the Earth surface respond. Due to propagation of GCR protons and electrons trough the heliosphere we observe the different classes of the variations of these particles directly associated with the similar changes of solar activity and solar wind. One of powerful variations of GCR intensity is the 11-year variation, which is inversely related with the similar changes of solar activity [4–5]. In [5] the existence of the time lag between the changes of the solar activity and the GCR intensity was found, and it was supposed that the modulation region of GCR should be large ($\sim$ 100 AU). This supposition was confirmed by the spacecrafts measurements [6–7]. In [8] it was found that the time lag between the changes of the solar activity and the GCR intensity, and the amplitudes of the GCR modulation significantly vary for different 11-year cycles. In [9] it was suggested that an index which incorporates the number of sunspot groups and their heliolatitudes could be used to interpret the changes of GCR intensity during the 11-year cycle (1958–1968). In [10] it was assumed that the major part of the 11-year variation are the results of the accumulative effects of the Forbush decreases. In [11] it was noted that the drift effects play a significant role in the GCR modulation process, however, other effects could be equally important. To explain the 11-year modulation of proton intensity a combination of drift and global merged interaction regions was included in time-dependent model [12]. A difference in the rigidity dependence of the 11-year modulation of GCR between the positive ($A > 0$) and the negative ($A < 0$) polarity periods of the solar magnetic cycle was found [13]; the rigidity dependence of the diffusion coefficient was flatter for the 11-year decrease from 1987 to 1990 than for the decrease from 1977 to 1981. So, in this approaching the effects of the scattering and drift of GCR particles in the IMF (consisting of the regular and turbulent components) are averaged and temporal changes of the character of the modulation of GCR intensity is ignored. In [14] it was shown that the overall behavior of GCR modulation by solar activity is basically similar within the energies to which neutron monitors respond for four recent solar activity cycles; however, there is a significant anomaly for the period of 1972–1977 (solar cycle 20). In [15] the features of the 11-year variations of GCR intensity were studied using the data of balloons measurements for the relatively low energy range (< 0.5 GeV); it is stated that the general properties of the long-period modulation of GCR intensity observed by the balloons measurement can be described based on the anisotropic diffusion model with drift. Recently, to explain the 11-year and 22-year variation of GCR protons, electrons and helium the propagating diffusion barrier with other general modulation mechanisms were included in the time-dependent model [16]. In [17–19] 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; moreover, according to [18–19] a change of the character of diffusion of GCR particles *versus* solar activity should be a general reason of the 11-year variation of the GCR intensity. The solar wind velocity is almost constant in the region of the low heliolatitudes ($\leq 35°$) during the 11-year cycle of solar activity [20] and, consequently, the convection of the GCR particles must not change noticeably *versus* the solar activity at the Earth orbit. The diffusion coefficient (according to the quasi linear theory) depends on the GCR particle's rigidity, and is defined by the structure of the IMF turbulence. As it is noted in [21–24] the dependence of the diffusion coefficient on the GCR particle's rigidity is significant among equally important dependencies of the diffusion coefficient on the other parameters of the solar activity and solar wind. In [18,19,25] it was shown that the temporal change of the diffusion coefficient of the GCR particles is related with the changes of the PSD in the energy range of the IMF turbulence *versus* the solar activity. For the diffusion-convection approximation the exponent γ of the rigidity R spectrum $\frac{\delta D(R)}{D(R)}\left(\frac{\delta D(R)}{D(R)} \propto R^{-\gamma}\right)$ of the GCR intensity variations generally is determined by the parameter α [26,27] showing the character of the dependence of the diffusion coefficient χ on the rigidity R of GCR particles ($\chi \propto R^{\alpha}$) [20–23,27]. The parameters α and ν are related as, $\alpha = 2 - \nu$ (ν is the exponent of PSD of the IMF turbulence (PSD $\propto f^{-\nu}$, where f is the frequency). Based on the experimental data analyses and theoretical modeling it was shown that an apparent relationship exists between the rigidity spectrum exponent γ of the GCR intensity variations and the exponent ν of the PSD of the IMF turbulence; namely, $\nu \approx 2 - \gamma$ [26,27,29]; the temporal changes of the exponent ν of the PSD in the energy range of the IMF turbulence (10^{-6}–10^{-5}) Hz is clearly manifested in the temporal changes of the rigidity spectrum exponent γ of the GCR intensity variations measured by neutron monitors. Also, it was found that, in general, the above mentioned relationship between γ and ν is valid not only for long-period variations but for the Forbush effects of GCR intensity [29,30]. Particularly, 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}–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}–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. A purpose of this paper is to obtain the temporal changes of the rigidity spectrum exponent γ of the GCR intensity variations using neutron monitors data and find its relationship with the sunspot numbers, the exponent ν of the PSD of the IMF turbulence, and GCR intensity for the period of 1960–2002.

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 $A < 0$ epoch (1960–2002). A criterion for the data selection was a continuous functioning 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: $J_i^k = \frac{N_0 - N_k}{N_0}$; N_k is the running monthly average count rate ($k = 1, 2, 3, \ldots,$ 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 list of neutron monitors used for the calculations (denoted by '+') and RP for the period to be analyzed are brought in Table I.

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 [31]:

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

where $\left(\frac{\delta D(R)}{D(R)}\right)_k$ is the rigidity spectrum of the GCR intensity variations for the k month and $W_i(R_i, h_i)$ is the coupling coefficient for the neutron component of GCR [31,32] $R_{\max}$ is the upper limiting rigidity beyond which the magnitude of the GCR intensity variation is vanished. For the power type of the rigidity spectrum $\left(\frac{\delta D(R)}{D(R)}\right)_k = A \cdot R^{-\gamma_k}$ one can write:

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

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.

TABLE I

Stations	Cut off rigidity [GV]	1960–1964 RP 1965	1966–1970 RP 1965	1971–1975 RP 1976	1977–1981 RP 1976	1982–1985 RP 1986	1988–1991 RP 1987	1992–1996 RP 1997	1998–2002 RP 1997
Apatity	0.65	−	−	−	−	−	−	−	+
Climax	3.03	+	+	+	+	+	+	+	+
Deep River	1.02	+	−	−	+	+	+	−	−
Goose Bay	0.52	−	−	−	+	+	+	+	−
Haleakala-Huancayo	13.4	+	+	+	+	+	+	+	+
Hermanus	4.90	−	+	−	+	+	+	−	+
Inuvik	0.18	−	+	+	+	+	+	+	−
Jungfraujoch	4.48	−	−	−	+	−	−	−	−
Kergulelen Is	1.19	−	−	+	−	−	−	−	−
Kiel	2.29	+	+	+	+	−	+	+	+
Mc Murdo	0.01	−	−	−	−	−	−	−	+
Moscow	2.46	+	+	+	+	+	+	+	+
Mt.Norikura	11.39	−	−	−	−	+	−	−	−
Mt.Washington	1.24	−	+	+	−	+	−	+	−
Pic-du-Midi	5.36	−	+	+	−	−	−	−	−
Potchefstroom	7.30	−	−	−	+	+	+	+	+
Rome	6.32	−	−	−	−	−	−	−	+
Tbilisi	6.91	−	−	−	+	+	+	−	−

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 [24–26]. 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 [30,32]. The upper limiting rigidity $R_{\max}$, beyond which the magnitude of the GCR intensity variation is vanished, equals 100 GV. This assumption is reasonable for the 11-year variation of the GCR intensity [13]. 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 to given number of neutron monitors (Table I), and the temporal changes of the rigidity spectrum exponent γ_k for all eight periods (Table I) 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 and the sunspot number are presented in Figs. 1(a), 1(b), 1(c) for the whole period of investigation (1960–2002).

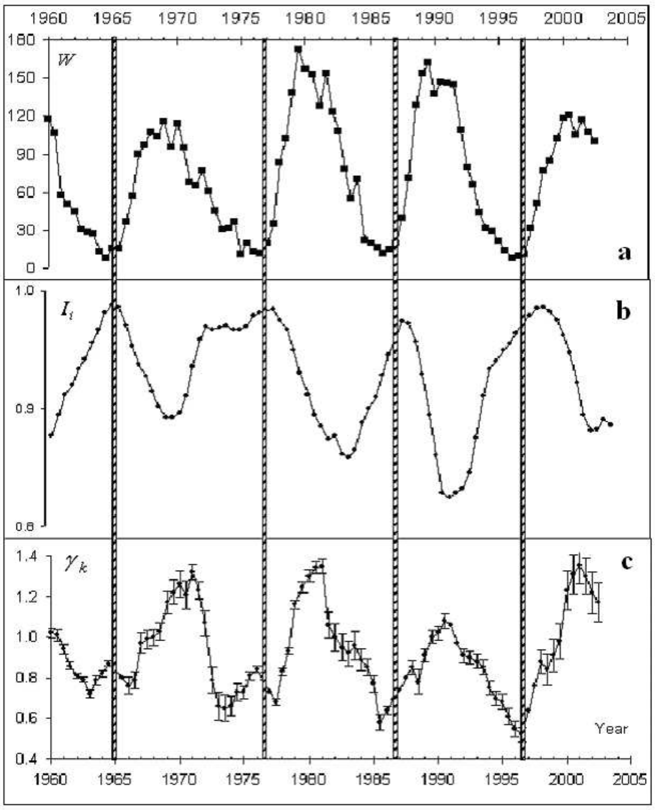

Fig. 1. The temporal changes of the smoothed semi-annual average (with the interval of 1.5 year) magnitudes for the whole period of investigation (1960–2002): (a) The sunspot number — W, (b) I_i of the GCR intensity variations by Climax neutron monitor data (normalized with respect maximum intensity of 1965), (c) The rigidity spectrum exponent γ_k.

Figs. 1(a), 1(b), 1(c) shows that a distinction between the temporal changes of the rigidity spectrum exponent γ_k for the $A>0$ and the $A<0$ polarity epoch is not recognizable; J_i^k anti correlates with the sunspot numbers W and the rigidity spectrum exponent γ. Correlation coefficients for four ascending and four descending periods of solar activity between the pairs:

sunspot numbers W and GCR intensity J, (W and J); GCR intensity J and rigidity spectrum exponent γ, (J and γ), and sunspot numbers W and rigidity spectrum exponent γ, (W and γ) are presented in Table II.

TABLE II

Time interval	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

Table II shows that the temporal changes of the rigidity spectrum exponent γ_k of long period variations of the GCR intensity show the well established 11-year variation to be in good correlation with the similar changes of the sunspot numbers; there is observed a high inversely correlation between changes of J and γ, and positive correlation between W and γ. According to our assumption it is related with the temporal changes of the exponent ν of the PSD of the IMF turbulence *versus* solar activity. So, we assume that for a magnetic field with a Gaussian distribution the power spectrum is sufficient to completely characterize the IMF turbulence [2]. To show a relationship between γ and ν the yearly average values of the rigidity spectrum exponent γ and the exponent ν of the PSD of the B_x, B_y, B_z components of the IMF turbulence (in the frequency range of $\sim$ (10^{-6}–10^{-5}) Hz were considered. The exponent ν was found using the IMF experimental data [27] for the period of 1976–2002. To increase the statistical accuracy smoothed yearly means (with the interval of 3 years) of the rigidity spectrum exponent γ and the exponent ν of the PSD of the B_y component of the IMF have been used. Components B_y and B_z of the IMF turbulence (perpendicular to the radial direction) insert the crucial contribution to the scattering of GCR particles in the heliosphere, although their roles are not equal at all. The power of the B_y component is significantly greater than the power of B_z component. According to the observed character of the relationship between γ and ν the considered period 1976–2002 could be divided into two different intervals, 1976–1989 and 1990–2002. The changes of the smoothed yearly values of the rigidity spectrum exponent γ (dashed) and ν (solid) of the PSD of the B_y component of the IMF turbulence for the period of 1976–2002 are presented in Figs. 2(a), 2(b).

Fig. 2(a) shows a high anti-correlation between ν and γ (correlation coefficient r equals -0.80 ± 0.20) for the period of 1976–1989, while a correlation between ν and γ is basically absent (correlation coefficient r equals -0.42 ± 0.31) for the period of 1990–2002 (Fig. 2(b)). We assume that either we do not fully understand global changes in the heliosphere since 1990–1991 up to 2002 / or the IMF with an ordinary Gaussian distribution alter into

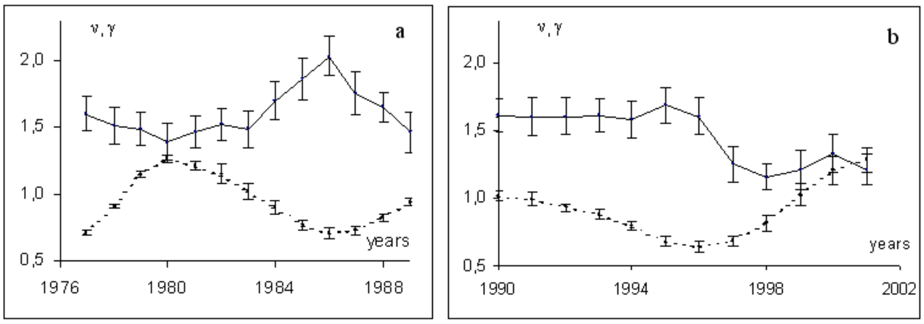

Fig. 2. The smoothed yearly values of the rigidity spectrum exponent γ (dashed) of the GCR intensity variations and ν (solid) of the PSD of the B_y component of the IMF turbulence for the period of 1976–1989 (a), and 1990–2002 (b).

e.g. well expressed lognormal distribution with the intermittence [33], and the power spectrum is not sufficient to completely characterize the IMF turbulence. Generally, a high correlation between γ and ν demonstrates that the IMF turbulence is quite isotropic (for example in 1976–1989); indeed, besides, *in situ* data of the IMF correspond to 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 2002 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 is formed. A detail study for the periods when the correlation coefficients are relatively less and change in the scope of $0.61 \leq r \leq 0.8$ is in the progress.

3. Summary

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 [25–27,29] 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 energy range (10^{-6}–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 5–50 GeV to which neutron monitors respond.

2. 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. This index can be successfully used for the estimation of the state of the IMF turbulence in the energy range (10^{-6}–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] K. Mursula, Th. Ulich, *Geophys. Res. Lett.* **25**, 1837 (1998).

[2] E.N. Parker, *Interplanetary Dynamical Processes*, Inter. Pub., New York–London 1963.

[3] E.C. Stone, A.C. Cummings, *at al.*, *Science* **309**, 2017 (2005).

[4] I.V. Dorman, L.I. Dorman, *J. Geophys. Res.* **72**, 1543 (1967).

[5] I.V. Dorman, L.I. Dorman, *Nauka (Moscow)* **65**, 100 (1967).

[6] Z. Fujii, F.B. McDonald, R.A. Caballero-Lopez, H. Moraal, Radial Intensity Gradients and Diffusion Coefficients of Cosmic Rays in the Outer Heliosphere at Solar Maximum, Proceedings of 28th ICRC, Japan, 2003, p. 3831.

[7] Z. Fujii, F.B. McDonald, *J. Geophys. Res.* **102**, 24201 (1997).

[8] K. Nagashima, J. Morishita, *Space Sci.* **28**, 195 (1980).

[9] Yu. Stozhkov, T.N. Charakchyan, *Geomagn. Aeron.* **9**, 803 (1969).

[10] J.A. Lockwood, W.R. Webber, *J. Geophys. Res.* **89**, 17 (1984).

[11] W.R. Webber, J.A. Lockwood, *J. Geophys. Res.* **93**, 8 (1988).

[12] J.A. Le Roux, M.S. Potgieter, *Astrophys. J.* **442**, 847 (1995).

[13] J.A. Lockwood, W.R. Webber, *J. Geophys. Res.* **101**, 21573 (1996).

[14] I.G. Usoskin *et al.*, *J. Geophys. Res.* **103**, 9567 (1998).

[15] G.A. Bazilevskaya, A.E. Svirzhevskaya, *Space Sci. Rev.* **85**, 431 (1998).

[16] S.E. Ferreira, M.S. Potgieter, *Astrophys. J.* **603**, 744 (2004).

[17] L.I. Dorman, *Adv. Space Res.* **27**, 601 (2001).

[18] M.V. Alania, R.G. Aslamazashvili, T.B. Bochorishvili, K. Iskra, M. Siluszyk, *Adv. Space Res.* **27**, 613 (2001).

[19] M.V. Alania, *Acta Phys. Pol. B* **33**, 1149 (2002).

[20] M.A. El-Borie, M.L. Duldig, J.E. Humble, Interplanetary Plasma and Magnetic Field Observations at 1 AU, Proceedings of 25th ICRC, Durban, South Africa 1997.

[21] J.R. Jokipii, *Rev. Geophys. Space Phys.* **9**, 27 (1971).

[22] I.N. Toptygin, Cosmic Rays in Interplanetary Magnetic Fields, D. Redel Publishing Company, Dordrecht 1985.

[23] J.W. Bieber, W.H. Mathaeus, C.W. Smith *et al.*, *Astrophys. J.* **420**, 294 (1994).

[24] Y.P. Melnikov, *Geomagn. Aeoron.* **45**, 445 (2005).

[25] M. Siluszyk, K. Iskra, R. Modzelewska, M.V. Alania, *Adv. Space Res.* **35**, 677 (2005).

[26] M.V. Alania, K. Iskra, *Adv. Space Res.* **16**, 241 (1995)

[27] M.V. Alania, K. Iskra, M. Siluszyk, *Adv. Space Res.* **32**, 651 (2003).

[28] L.A. Fisk, M.L Goldstein, A.J. Klimas, *et al.*, *Astrophys. J.* **190**, 417 (1974).

[29] M.V. Alania, 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, 2003, p. 3881.

[30] A. Wawrzynczak, M.V. Alania, *Adv. Space Res.* **35**, 682 (2005).

[31] L.I. Dorman, Variations of Galactic Cosmic Rays, Moscow, Izdatel'stvo Moskovskogo Universiteta, 1975, p. 214, in Russian.

[32] S. Yasue, *et al.*, Coupling Coefficients of Cosmic Rays Daily Variations for Neutron Monitors, 7, Nagoya 1982.

[33] L.F. Burlaga, *J. Geophys. Res.* **106**, 15917 (2001).