Rigidity spectrum of the long-period variations of the galactic cosmic ray intensity in different epochs of solar activity

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Abstract. We investigate character of correlations between the rigidity spectrum exponent γ of the 11-year variations of the Galactic Cosmic Ray (GCR) intensity and the exponent ν of the Power Spectral Density (PSD) of the Interplanetary Magnetic Field (IMF) turbulence in period 1968-2012 using data of the IMF and carefully selected neutron monitors. We show that a clear inversely correlation between γ and ν is observed when a resonance frequency range f_1–f_2 of the IMF turbulence (using for calculation of ν), are determined taking into account changes of the solar wind velocity V_{sw} and strength B of the IMF versus solar activity. We assume that an essential contribution to the scattering of GCR particles in the heliosphere is setting up generally by the turbulence of B_y and B_z components of the IMF. Therefore, in this paper we use the exponents ν_y and ν_z of PSD of the B_y and B_z components of the IMF turbulence. Generally, both γ and ν can be accepted as the essential proxies to study GCR propagation near earth orbit in heliosphere for the rigidity range of GCR particles to which neutron monitors and ground muon telescopes respond

1. Introduction and Motivation

In [1], [2] and [3] have demonstrated that about 75–80% changes of amplitudes of the 11-year variations of the Galactic Cosmic Ray (GCR) intensity measured by neutron monitors can be explained in the first approximation by the anisotropic diffusion–convection model of GCR transport. Consequently, if that is the case, changes of the solar wind velocity and diffusion coefficient should play a vital roles in formation of the 11–year variation of the GCR intensity near earth orbit in heliosphere. On the other, data of the solar wind velocity does not show any regular valuable changes versus the 11–year cycle of solar activity. So, contributions of the convection and adiabatic cooling of the GCR particles (directly related with the solar wind velocity) in long period variation of the GCR intensity can be basically ignored. Thus, one can declare that a character of diffusion of the GCR particles versus solar activity should play an important role in the formation of the 11–year variation of the GCR intensity. However, if that is so, there exists a natural question, what of the parameters characterized solar wind and solar activity contributed in complex changes of diffusion coefficient can be generally responsible for the alternation of diffusion coefficient versus solar activity. In order to answer to this essential question we have to take into account one of the vital arguments, a peculiarity of the temporal changes of the power law rigidity R spectrum exponent γ ($\delta D(R)/D(R) \propto R^{-\gamma}$, $D(R)$ is GCR primary spectrum) of the amplitudes of the 11–year variations of the GCR intensity measured by neutron monitors.

We have found in [2], [3], [4], [5] and [6] that the exponent γ is larger (γ=1.2±0.1) in the maxima epochs (rigidity spectrum is soft) than in minima epochs (γ=0.6 ±0.1) of solar activity (rigidity spectrum is hard).

We also have established that an exponent ν of the Power Spectral Density (PSD) of the Interplanetary Magnetic Field (IMF) turbulence (In resonance frequency range f_1–f_2, to which neutron monitors respond) varies versus solar activity. Also, temporal changes of exponents γ and ν versus solar activity are in clear inversely correlation. Thus, we have two very essential physically reasonable parameters, (1) the rigidity spectrum exponent γ of GCR variations, and (2) the exponent ν of the PSD of the IMF turbulence. Thus, one can declare that both γ and ν can be accepted as the very essential proxies to study GCR propagation near earth orbit in heliosphere. Other than, despite we find an apparent correlation between changes γ and ν based on the experimental data of neutron monitors and IMF, there is a question of interest what is the theoretically expected relationship between changes of γ and ν based on the modelling of GCR transport in heliosphere.

We have numerically solved in [3], [5] and [6] transport equation next in turn for physically acceptable changes of parameters included in parallel diffusion coefficient in [7]. We found that the similar relationships between γ and ν obtained by experimental data of neutron monitors and IMF turbulence is gained from theoretical modelling when parallel diffusion coefficient K_{II} depends on the parameter R^{α} ($K_{II} \propto R^{\alpha}$, where $\alpha=2-\nu$) [11]. So, one can conclude that a changeable IMF turbulence versus solar activity plays a decisive role in creation of the 11–year variation of GCR intensity.

An essential contribution to the scattering of GCR particles in the heliosphere is generally setting up by the turbulence of B_y and B_z components of the IMF in [7], [8] and [3], although quantitative contributions each of them in creation of the electromagnetic conditions at the near earth orbit in heliosphere are different. In spite, between the temporal changes of the exponents ν_y and ν_z there is a precious correlation, the average power P of the PSD of the B_y component is about twice larger than the average power of the B_z component in [3]. In paper [9] we have studied the time interval 1968–2002 dividing it into three successive periods: 1968–1976 (I), 1977–1989(II), and 1990–2002(III). We used data of neutron monitors, B_y and B_z components of the IMF, and sunspot numbers. We have compared changes of an annual values of exponent γ, and ν_y and ν_z *for* each three periods. Results are presented in figure 1 of paper [9]. We have found a clear inversely correlation between γ and ν_y and between γ and ν_z in period 1977–1989; however for periods 1968–1976 and 1990–2002 relations between γ and ν_y, and between γ and ν_z are not so substantial.

It should be noted that the annual average values of ν_y and ν_z of the PSD of the B_y and B_z components of the IMF were calculated in [9] for the same constant frequency interval $\Delta f= f_2-f_1=3^x10^{-6}Hz$ (from here called as the first method). Calculations of the constant frequencies $f_1=1x10^{-6}Hz$ and $f_2=4^x10^{-6}Hz$ were carried out using the constant solar wind velocity $V_{sw}=432.4$ *km/s* and the constant strength $B=4.6nT$ of the IMF for the whole period 1968–2002. So, the frequencies f_1 and f_2 which determine the frequency intervals $\Delta f=f_2-f_1\approx(3\text{-}4)x10^{-6}Hz$ of the IMF turbulence (responsible for the scattering of GCR particles to which neutron monitors respond) are considered as the constants for the whole period 1968–2002 including a few 11–year cycles of solar activity. On the other, the solar wind velocity V_{sw} and strength B of the IMF vary from year to year for the whole period 1968–2002, and correspondingly the resonant frequencies f_1 and f_2 using for calculation of the interval Δf are changed. Therefore, it is of interest how changes correlations between (γ and ν_y) and between (γ and ν_z) are calculated for the frequency intervals $\Delta f=f_2-f_1\approx(3\text{-}4)x10^{-6}Hz$ obtained based on the alternated magnitudes of the solar wind velocity V_{sw} and strength B of the IMF from year to year (from here called as the second method). Here we consider last solar cycle #23 with unusual prolonged minimum. We calculated when ν_y and ν_z using the second method. A purpose of this paper is to carry on a study of relations between (γ and ν_y) and between (γ and ν_z) in the period 2002–2012 consisting of the ending epoch of the unusual minimum period of the 11–year solar cycle #23 and the beginning of solar cycle #24. The period 2002–2012 will be further called as the fourth (IV) period of the whole time interval 1968–2012.

Thus, our analyse will be dealt to investigate relations between (γ and ν_y) and between (γ and ν_z) in the time interval 1968–2012 consisting of four successive periods: 1968–1976(I), 1977–1989(II), 1990–2002(III), and 2003–2012(IV).

2. Experimental Data and discussion

We present in figures 1ab changes of the solar wind velocity V_{sw} (figure 1a) and the strength B of the IMF (figure 1b) for period 1968–2012. Figures 1ab show that the strength B has a noticeable quasi 11–year periodicity, while this periodicity is absent in the changes of the solar wind velocity V_{sw}.

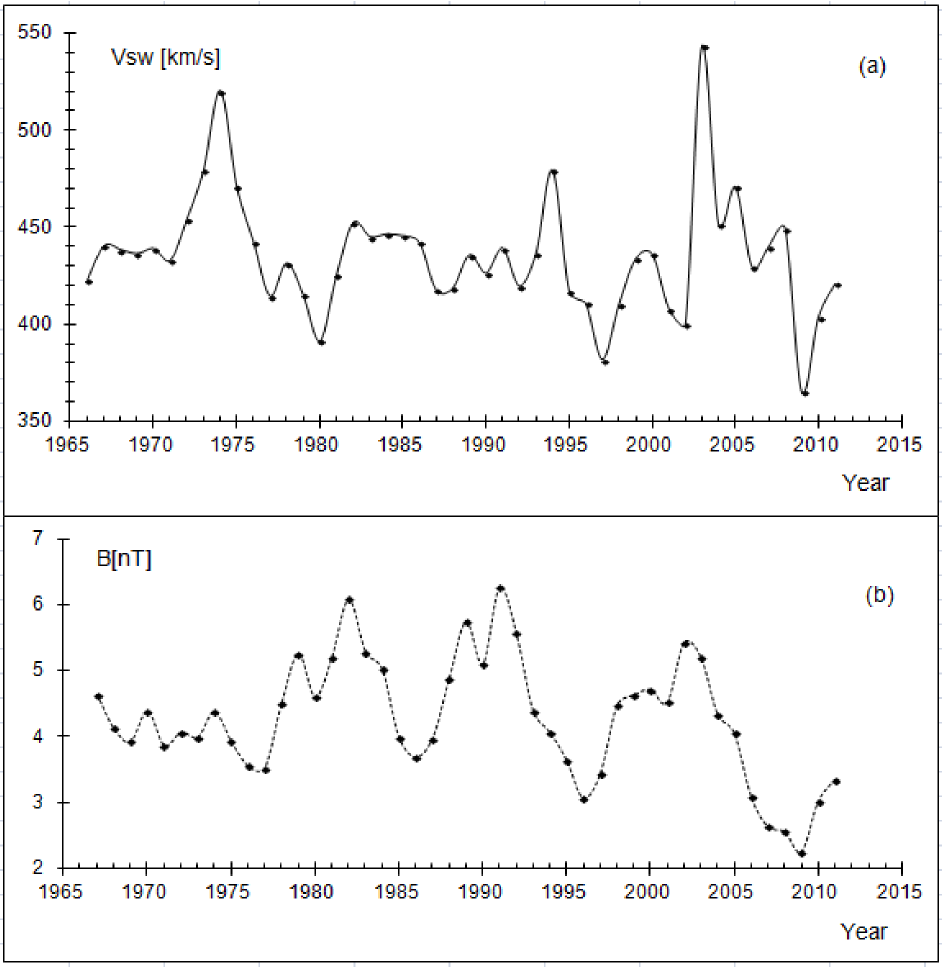

Figure 1ab. Temporal changes of the solar wind velocity V_{sw} (a) and strength B of the IMF (b) in 1968 – 2012.

To calculate a resonant frequencies f_{res} and corresponding frequency intervals Δf for changeable V_{sw} and B upon solar activity we employ the formula $f_{res} = \frac{300}{2\pi}\frac{V_{SW} \cdot B}{R}$ from [7]. We used for calculations yearly averages of the solar wind velocity V_{sw}, the strength B of the IMF and rigidity of GCR particles in GV. Temporal changes of the f_{res} for rigidity 10 GV of GCR particles are presented in figure 2.

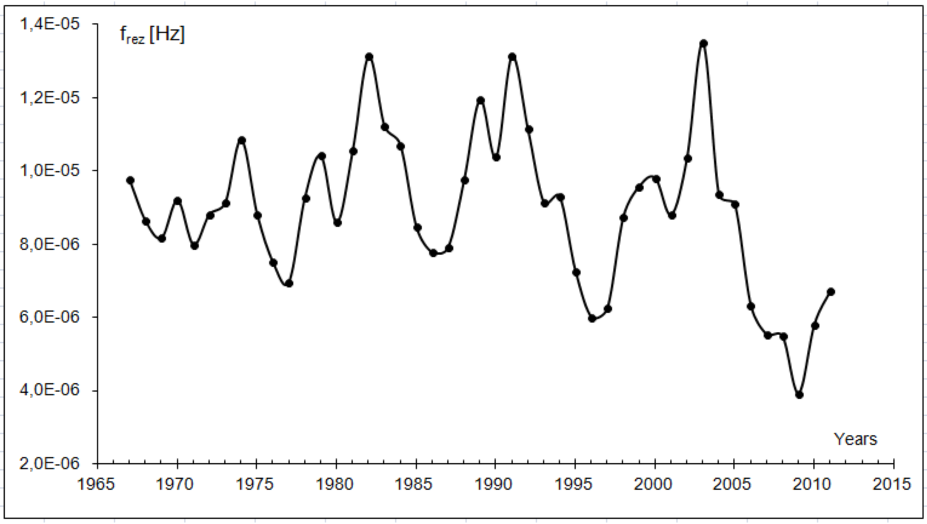

Figure 2 Annual changes of the resonant frequency f_{res} for rigidities 10 GV of GCR particles in different period of solar activity from 1968 to 2012.

Comparing figures 1ab and figure 2 one can recognize that changes of B from year to year which has clearly expressed quasi 11–year cycling, is responsible for time profile of f_{res}, while the role of solar wind velocity is not significant. Correlation coefficient r between f_{res} and B is equal to 0.95 ± 0.01, but between f_{res} and U_{sw} that is equal to 0.31 ± 0.03.Resonant frequencies and corresponding intervals $\Delta f = f_1 – f_2 = \sim(3–4)^x 10^{-6} Hz$ for changeable V_{sw} and B in period 1968–2012 are presented in table 1.

Table 1. Frequency ranges Δf determined for period 1968 to 2012.

No.	Periods	Frequency range [Hz]	Δf [μHz]
I	1968	7.9*10^-7---3.8*10^-6	3,0
	1969-1970	2.1*10^-6---5.8*10^-6	3,7
	1971-1975	7.9*10^-7---3.8*10^-6	3,0
	1976-1977	7.6*10^-7---3.8*10^-6	3,0
II	1978-1980	1.7*10^-6---5.8*10^-6	4,1
	1981-1982	1.0*10^-6---4.0*10^-6	3,0
	1983	1.7*10^-6---5.8*10^-6	4,1
	1984-1987	7.6*10^-7---3.8*10^-6	3,0
	1988	1.0*10^-6---4.0*10^-6	3,0
III	1989-1992	1.7*10^-6---5.8*10^-6	4,1
	1993-1998	7.0*10^-7---3.7*10^-6	3,0
	1999-2000	1.7*10^-6---5.2*10^-6	3,5
	2001	1.0*10^-6---4.0*10^-6	3,0
	2002	1.7*10^-6---5.2*10^-6	3,5
IV	2003-2005	7.0*10^-7---3.7*10^-6	3,0
	2006	4.1*10^-7---3.0*10^-6	2,6
	2007	4.4*10^-7---3.0*10^-6	2,5
	2008	4.1*10^-7---2.8*10^-6	2,6
	2009	4.1*10^-7---3.5*10^-6	3,1
	2010-2012	1.0*10^-6---4.0*10^-6	3,0

We assume that an essential contribution to the scattering of GCR particles in the heliosphere is generally setting up by the turbulence of B_y and B_z components of the IMF, so for investigation we use in this paper exponents ν_y and ν_z of PSD of the B_y and B_z components of the IMF. Disposing resonant frequencies f_{res} and frequency intervals Δf (see table 1) of the turbulence of the IMF (which are responsible for scattering of GCR particles to which NM respond) we have calculated the corresponding annual values of the exponents ν_y and ν_z. Changes of the rigidity spectrum exponent γ (solid blue line), and exponents ν_y of the PSD of the IMF turbulence calculated by the first method (dot black line) and by the second method (dashed red line) in periods I, II, III and IV are presented in figure 3; the same but for ν_z are presented in figure 4.

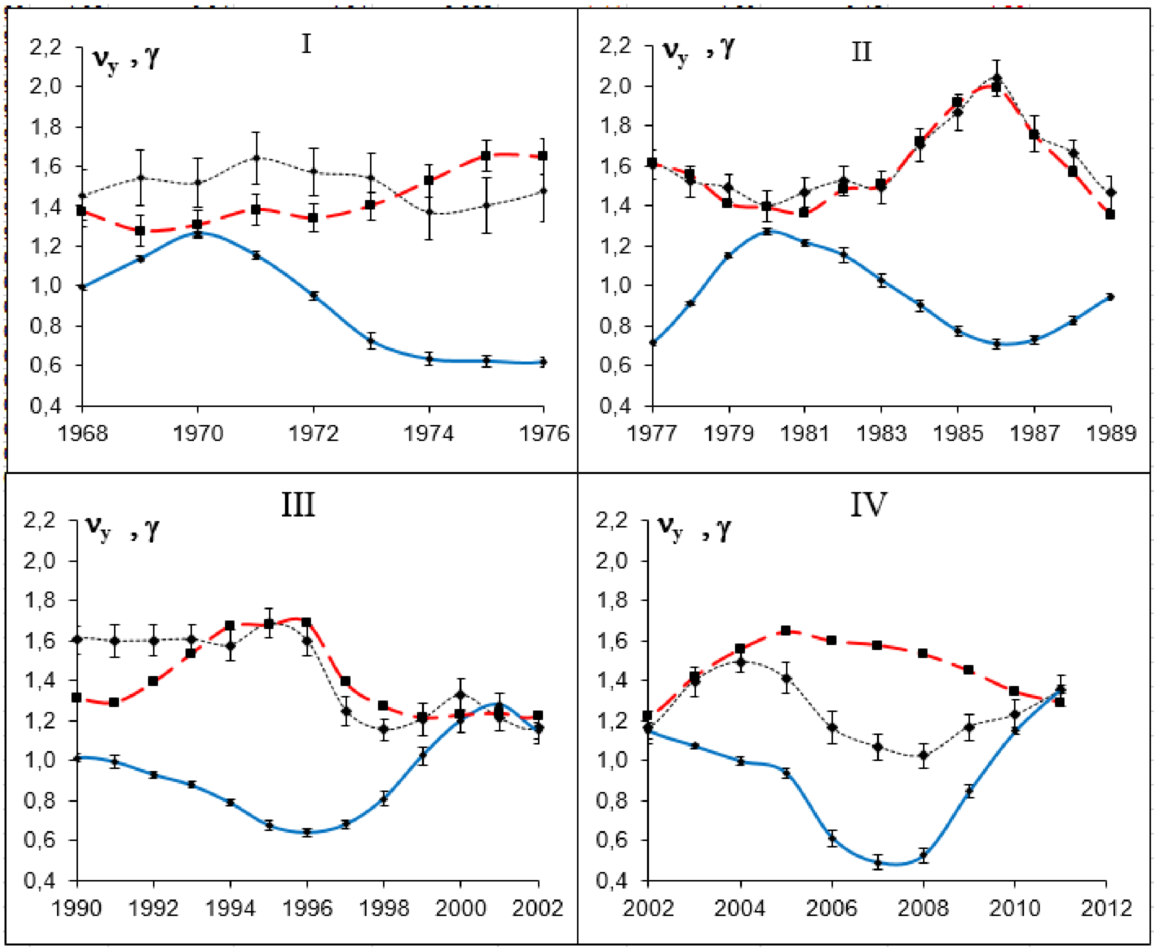

Figure 3. Temporal changes of the rigidity spectrum exponent γ (solid blue line) and exponents ν_y calculated by the first method (dot black line) and by the second method (dashed red line) in periods I, II, III and IV.

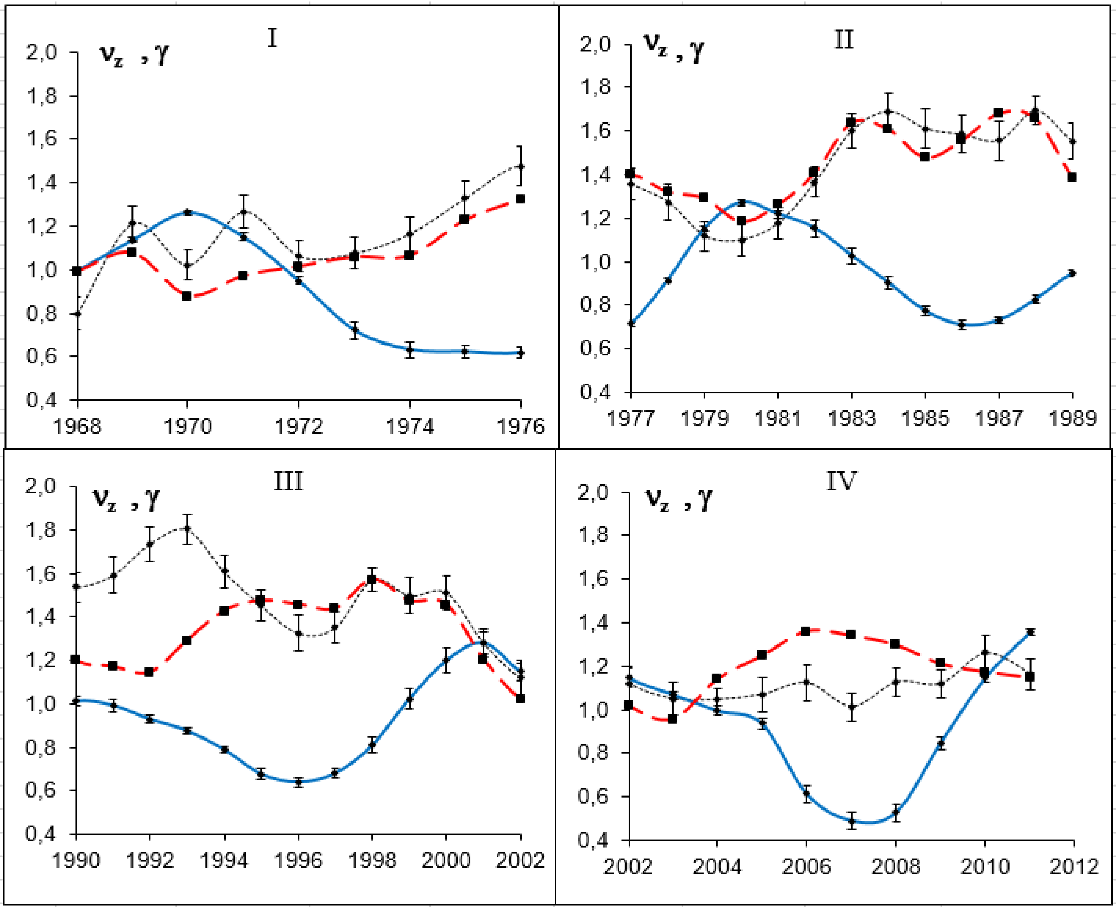

Figure 4. Temporal changes of the rigidity spectrum exponent γ (solid blue line), and exponents ν_z calculated by the first method (dot black line) and by the second method (dashed red line) in periods I, II, III and IV.

To more detail study of relations between (γ and ν_y) and between (γ and ν_z), we calculate correlation coefficients r_1 (γ ; ν_y) and r_1(γ ; ν_z) when the values ν_y and ν_z were obtain by the first method and r_2(γ ; ν_y) and r_2 (γ ; ν_z) calculated by the second method for periods: I, II, III and IV for whole analysed period 1968–2012. Results are presented in table 2.

Table 2. Correlation coefficients r_1 and r_2 between (γ and ν_y) and between (γ and ν_z)

	Period	r_1 (γ ; ν_y)	r_2 (γ ; ν_y)	r_1 (γ ; ν_z)	r_2 (γ ; ν_z)
I	1968-1976	0.64 ± 0.17	-0.86 ± 0.11	-0.43 ± 0.20	-0.78 ± 0.14
II	1977-1989	-0.78 ± 0.11	-0.78 ± 0.11	-0.69 ± 0.13	-0.66 ± 0.13
III	1990-2002	-0.43 ± 0.16	-0.78 ± 0.12	-0.19 ± 0.18	-0.54 ± 0.15
IV	2003-2012	0.72 ± 0.16	-0.73 ± 0.13	0.41 ± 0.17	-0.74 ± 0.14

A high inverse correlation is observed in 1977–1989 (the II period, solar cycle 21) between temporal changes of (γ and ν_y) and between (γ and ν_z). A level of high correlation does not depend whether the ν_y and ν_z are calculated by the first method or by the second method. At the same time a clear inverse correlation takes place between temporal changes of (γ and ν_y) and (γ and ν_z) for shifted frequency range versus solar activity corresponding to the alternation of resonant frequencies in periods I, III and IV (solar cycles: # 20, # 22 and #23/24). Likely, 11–year solar cycles from point of view of the IMF turbulence structure are really individual. An existence of an inverse correlation between γ and ν during solar cycles #20, #22 and #23/24 for shifted resonant frequencies versus level of solar activity should be considered as a normal phenomenon matching to the theory of scattering of GCR particles in heliosphere. However, the solar cycle #21, when an inverse correlations between (γ and ν_y) and between (γ and ν_z), are high and do not depend on the IMF strength alternation versus solar activity should be considered as an exclusion one.

We demonstrate that changes of ν_y and ν_z versus solar activity play a central role in the formation of the features of the long period variations of the GCR intensity, especially its rigidity dependence. Thus, one can conclude that inverse relations between (γ and ν_y) and between (γ and ν_z) are regular. We consider that the found relations are expected from the QLT for GCR particles to which neutron monitors respond [7] and [10].

Summary

1. We believe that temporal changes of the exponents ν_y and ν_z of the PSD of the IMF obtained by in situ measurement of B_y and B_z components in local space satisfactorily reflects the average structure of the IMF turbulence in the vicinity of the heliosphere where modulation of the long period variations of the GCR intensity takes place; both ν_y and ν_z have clearly expressed 11–yr cycling and can be considered as the central parameters shedding light on the modulation of GCR in the range of rigidity of cosmic ray particles to which neutron monitors respond.
2. We find that for the GCR particles of rigidity 10 GV the resonant frequencies regularly are lower in minimum than in maximum epochs of solar activity for 1968–2012; in these changes a decisive role belongs to quasi 11–yr cycle of the strength B of the IMF.
3. The significant high inverse correlation is observed between temporal changes of (γ and ν_y) and between (γ and ν_z) in 1977–1989 (solar cycle # 21). A range of correlation does not depend whether the ν_y and ν_z are calculated for constant B and U_{sw} corresponding to average resonant frequencies for individual ascending and descending periods or for alternated of resonant frequencies of the IMF turbulence versus solar activity. So, ν_y and ν_z are unchanging when a range of frequency $\Delta f = \tilde{}(3–4)^x 10^{-6}$ *Hz* is sliding versus time during #21 solar cycle. Possible, a turbulence of the IMF during the solar cycle #21 can be characterized as the completely homogeneous and highly isotropic.
4. At the same time for the solar cycles #20, #22, and #23/24 a clear inverse correlation between (γ and ν_y) and between (γ and ν_z) take place for shifted frequency range versus solar activity corresponding to the alternation of resonant frequencies of turbulence.
5. We assume that an existence of an inverse correlation between γ and ν during the solar cycles #20, #22, and #23/24 for shifted resonant frequencies versus level of solar activity should be considered as a normal case matching to the theory of scattering of GCR particles in interplanetary space; however, the solar cycle #21, when an inverse correlation between γ and ν is high and does not depend on the IMF strength alternation versus solar activity should be considered as an exclusion event.

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http://spidr.ngdc.noaa.gov/spidr/,
http://omniweb.gsfc.nasa.gov/index.html,
http://cr0.izmiran.rssi.ru/moscow/main.htm
http://www.nmdb.eu

References

[1] Dorman L I 2001 *Adv. Space Res.* **27** 601
[2] Alania M V 2002 *Acta Phys. Polonica B* 33 **4** 1149
[3] Alania M V, Iskra K and Siluszyk M 2010 *Adv. Space Res.* **45** 1203
[4] Alania M V, Iskra, K 1995, *Adv. Space Res.* 16 **9** 241
[5] Alania M V, Iskra K and Siluszyk M 2008a *Adv. Space Res.* **41** 26
[6] Alania M V, Iskra K and Siluszyk M 2008b *Acta Phys. Polonica B* 39 **11** 2961
[7] Jokipii J R 1971 *Rev. of Geoph. and Space Physics*. **9** 27
[8] Bieber J W, Mathaeus W H and Smith C W 1994 *Astrophys. J* **420** 294
[9] Siluszyk M, Iskra K and Alania, M V 2014 *Solar Physics* 289 **11** 4297
[10] Shalchi A 2009 *Nonlinear Cosmic Ray Diffusion Theories*, Springer, Berlin 180
[11] Siluszyk M, Wawrzynczak A and Alania M V 2011 *J. of atm. and S-T Physics* 73 **13** 1923