

# On relationship of the temporal changes of the rigidity spectrum of the galactic cosmic rays intensity variations and parameters of the interplanetary magnetic field turbulence

Michael V. Alania<sup>\*†</sup>, Krzysztof Iskra<sup>\*</sup> and Marek Siluszyk<sup>\*</sup>

<sup>\*</sup>*Institute of Math. And Physics of University of Podlasie, Siedlce, Poland*

<sup>†</sup>*Institute of Geophysics, Georgian Academy of Sciences, Tbilisi, Georgia*

**Abstract.** We study a relationship of the rigidity spectrum exponent  $\gamma$  of the galactic cosmic rays (GCR) intensity variations and the structure of the interplanetary magnetic field (IMF) turbulence using data of neutron monitors and the components Bx, By, Bz of the IMF in period of 1967-2002. The exponent  $\nu$  of the power spectral density (PSD) of the IMF turbulence in the range of the frequencies  $10^{-6}$ - $10^{-5}$  Hz increases when the rigidity spectrum of the GCR intensity variations is hard (in the minima epochs of solar activity), and decreases when it is soft (in the maxima epochs of solar activity). We demonstrate that there exist valuable correlations between rigidity spectrum exponent  $\gamma$ , exponent  $\nu$  and average amplitude of the PSD of the IMF turbulence throughout of the 11-year cycle of solar activity. We believe that the essential rearrangement of the structure of the IMF turbulence takes place 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  $> 1$  GeV.

**Keywords:** rigidity spectrum, power spectral density, interplanetary magnetic field turbulence

## I. INTRODUCTION

We accept that the rigidity R spectrum  $\frac{\delta D(R)}{D(R)}$  of the 11-year variations of the GCR intensity has a power law character with the exponent  $\gamma$ , as [1]:

$$\frac{\delta D(R)}{D(R)} = A \cdot R^{-\gamma}$$

Where A is the power of the rigidity spectrum. We studied a relationship between the rigidity spectrum exponent  $\gamma$  and the exponent  $\nu$  of the PSD of the IMF turbulence in the range of frequency  $f \approx 4 \cdot 10^{-6}$ - $10^{-5}$  Hz, (PSD  $\propto f^{-\nu}$ ) in papers [2, 3] for different periods of solar activity. We found that the temporal changes of the rigidity spectrum exponent  $\gamma$  should be considered as one of the important indexes to describe the 11-year variation of the GCR intensity. Our aim in this paper is to study the relationships among parameters  $\gamma$ ,  $\nu$ , and the power  $P$  of the PSD of the IMF turbulence, and clarify reasons of the noticeable distinctions of the correlations between  $\gamma$  and  $\nu$  in different separate periods to be analyzed. Also, we calculate the parallel

diffusion coefficient using the temporal changes of the exponent  $\nu$ , and PSD of the IMF turbulence from the maximum to the minimum epochs of solar activity.

## II. EXPERIMENTAL DATA AND DISCUSSION

We use data of selected neutron monitors [3], relative sunspot numbers  $W$  [4], rigidity spectrum exponent  $\gamma$  for the period of 1960-2002 [2, 3], and the power  $P$  of the PSD of the components Bx, By, Bz of the IMF turbulence calculated for the period of 1967-2002. In order to increase the statistical accuracy, yearly means of the rigidity spectrum exponent  $\gamma$ , exponent  $\nu$  and the power  $P$  of the PSD of the IMF turbulence of the Bx, By and Bz components of the IMF were smoothed with the running interval of 3 years. In Fig. 1 are presented the smoothed semi annual changes of the relative sunspot numbers ( $W$ , upper panel), the GCR intensity variations by Climax neutron monitor data normalized with respect to the maximum intensity of 1965 ( $J$ , middle panel), the rigidity spectrum exponent  $\gamma$  of the long-period variations of the GCR intensity ( $\gamma$ , middle panel) for the period of 1960-2002, and the power  $P$  of the PSD of the Bx, By, Bz components of the IMF turbulence for the period of 1967-2002 ( $P$ , bottom panel). The power  $P$  of the PSD of the Bx, By, Bz components of the IMF turbulence correspond to the average frequency  $\bar{f} = 7 \cdot 10^{-6}$  Hz of the frequency range  $f = 4 \cdot 10^{-6}$ - $10^{-5}$  Hz, to which neutron monitors respond.

Figure 1 shows the suppressing long period ( $\sim 11$ -year) changes of all considered parameters, though some less significant short period fluctuations are observed, too. A distinction between the temporal changes of the rigidity spectrum exponent  $\gamma$  for the  $A > 0$  and the  $A < 0$  polarity epochs is not recognizable. Correlation coefficients between the pairs: sunspot numbers  $W$  and GCR intensity  $J$ , ( $W \& J$ ); GCR intensity  $J$  and rigidity spectrum exponent, ( $J \& \gamma$ ), and sunspot numbers  $W$  and rigidity spectrum exponent, ( $W \& \gamma$ ) are presented in Table.

TABLE I: Correlation table between:  $J$ ,  $W$ ,  $\gamma$

Time interval	1967-1976	1977-1990	1991-2002
$J \& \gamma$	-0.95 $\pm$ 0.07	-0.64 $\pm$ 0.16	-0.78 $\pm$ 0.15
$W \& J$	-0.86 $\pm$ 0.13	-0.65 $\pm$ 0.15	-0.91 $\pm$ 0.10
$W \& \gamma$	0.90 $\pm$ 0.11	0.72 $\pm$ 0.14	0.60 $\pm$ 0.19

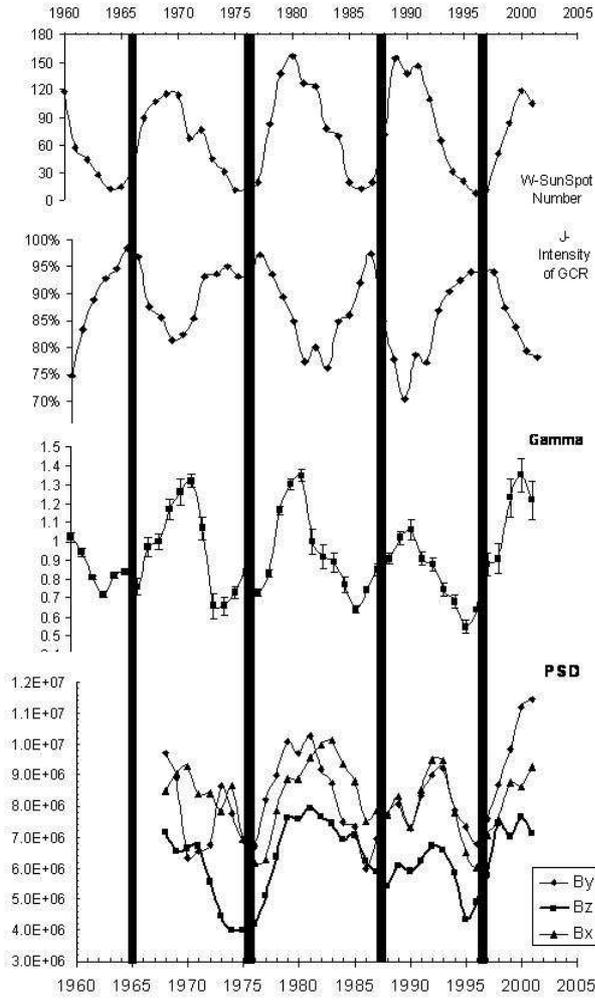


Fig. 1: Changes of the smoothed semi annual relative sunspot numbers ( $W$ , upper panel), the GCR intensity variations by Climax neutron monitor data normalized with respect to the maximum intensity of 1965 ( $J$ , middle panel), the rigidity spectrum exponent  $\gamma$  of the long-period variations of the GCR intensity ( $\gamma$ , middle panel) for the period of 1960-2002, and the power  $P$  of the PSD of the Bx, By, Bz components of the IMF ( $P$ , bottom panel) for the period of 1967-2002.

Table shows an existence of the high positive correlation between the changes of the exponent  $\gamma$  and sunspot numbers  $W$ , and negative correlation between changes of the exponent  $\gamma$  and the GCR intensity  $J$ .

The crucial contribution to the scattering of GCR particles in the heliosphere is setting up by the components By and Bz of the IMF turbulence perpendicular to the radial direction [5, 6]; although roles each of them are not equal at all. The power  $P$  of the PSD of the By component is greater than for the Bz component (about 1.5 times), but the temporal changes of the exponents  $\nu_y$  and  $\nu_z$  are in good correlation. In this paper we study the relationship between the exponent  $\nu_y$  of the PSD of the By component of the IMF turbulence and the exponent

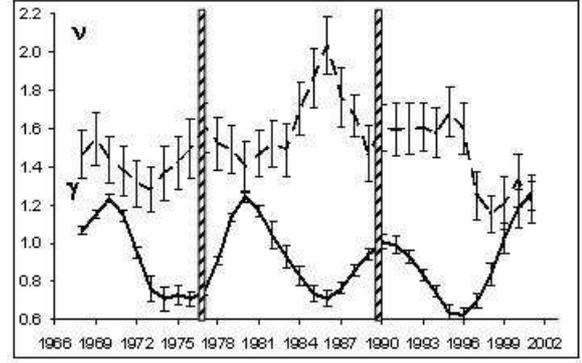


Fig. 2: The changes of the rigidity spectrum exponent  $\gamma$  and the exponent  $\nu_y$  of the PSD of the By component of the IMF turbulence for the period of 1966-2002.

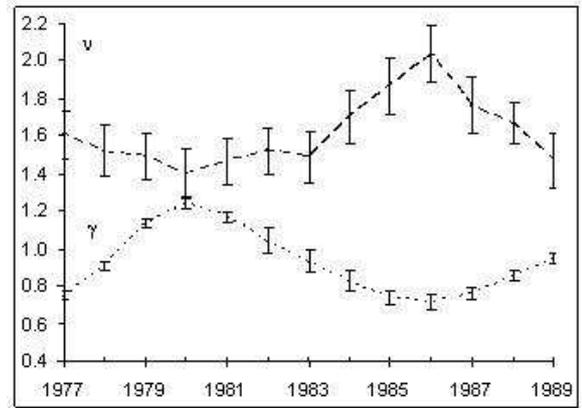


Fig. 3: The changes of the rigidity spectrum exponent  $\gamma$  and the exponent  $\nu_y$  of the PSD of the By component of the IMF turbulence for the period of 1977-1989.

$\gamma$  of the rigidity spectrum of the 11-year variations of the GCR intensity. The changes of the smoothed yearly values of the exponents  $\gamma$  and  $\nu_y$  are presented in fig.2 for the period of 1967-2002. Fig.2 shows an obvious 11-year quasi periodicity in the changes of the rigidity spectrum exponent  $\gamma$ , while the exponent  $\nu_y$  does not show similar regular 11-year cycling, exception for the period of 1977-1990 (Fig.2).

Taking into account a character of the relationship between the exponents  $\gamma$  and  $\nu$  for the separate time intervals, we divided 1967-2002 into three periods, 1967-1976, 1977-1989, and 1990-2002. Fig.2 shows a remarkable anti correlation between  $\gamma$  and  $\nu_y$  during the period of 1977-1989, while a clear correlations are not observed in the periods of 1967-1976, and 1990-2002. To shed light on these peculiarities, we analyze these three intervals separately. The temporal changes of the exponents  $\gamma$  and  $\nu_y$  for the period of 1977-1989 are presented in Fig.3

Fig.3 shows an excellent anti correlation between the exponents  $\gamma$  and  $\nu_y$  ( $r=-0.80\pm 0.16$ ). We think that a clear anti correlation between  $\gamma$  and  $\nu_y$  is observed due to the isotropic turbulence of the IMF in the whole

vicinity of the interplanetary space where the formation of the rigidity spectrum of the GCR intensity variations takes place. The exponent  $\nu_y$  obtained by local in situ measurement corresponds to the average condition of the IMF turbulence in this whole vicinity of the space, i.e., the IMF turbulence is isotropic and the roles of the intermittence /or anisotropy of the IMF turbulence are negligible. In doing so, the isotropic IMF turbulence could have a Gaussian distribution and the parameters of the PSD should completely characterize the IMF turbulence [7]. In this case, the scattering of the GCR particles can be described by the quasi linear theory (QLT) [6, 9, 10]. Diffusion coefficient  $K$  depends on the GCR particle's rigidity  $R$ , as  $K \propto R^\alpha$ , where  $\alpha = 2 - \nu$ ; on the other  $\gamma \propto \alpha$  [2.3], and there is expected a remarkable anti correlation between the exponents  $\gamma$  and  $\nu_y$ , as it is really observed by the experimental data in the period of 1977-1989 (Fig.3).

In view of discussion dealt with the period of 1977-1989 (with high correlation between  $\gamma$  and  $\nu_y$ ) it is of interest, how to interpret a violation of the relationship between  $\gamma$  and  $\nu_y$  in the periods of 1967-1976 (correlation coefficient  $r=0.32 \pm 0.25$ ), and 1990-2002 (correlation coefficient  $r=-0.27 \pm 0.26$ ). We assume that in this periods in situ measurements of the IMF do not correspond to the average state of the IMF turbulence in the whole vicinity of the interplanetary space where the formation of the rigidity spectrum of the GCR intensity variations takes place. The reasons of the violation of the relationship between exponents  $\gamma$  and  $\nu$ , can be an anisotropy character of the IMF turbulence/or, an existence of the intermittence of the IMF turbulence in the part of the space where in situ measurements of the IMF have carried out. In doing so, we ascribe an important role to the exponent  $\gamma$  which should determine an average state of the IMF turbulence in the whole vicinity where formation of the rigidity spectrum of the long period variations of the GCR intensity takes place. This statement is support by the high correlation ( $r=0.78 \pm 0.07$ ) between quasi periodic changes ( $\sim 11$ -year) of the rigidity spectrum exponent  $\gamma$  of the GCR intensity and the relative sunspot numbers  $W$  observed for whole considered time interval 1967-2002, besides between the exponents  $\gamma$  and  $\nu$ , there is observed very high correlation only in the period of 1977-1989, and any clear correlations are not observed in 1967-1976, and in 1990-2002.

Then, we assume that the relationship between the exponents  $\gamma$  and  $\nu$  in the period of 1977-1989 (correlation coefficient  $r=-0.80 \pm 0.16$ ), with corresponding regression equation  $\nu = -0.85 \cdot \gamma + 2.4$  is valid for the considered period of 1967-2002. This regression equation gives a possibility to estimate the exponent  $\nu$  as an average characteristic of the IMF turbulence of the whole vicinity of the space in the periods 1967-1976, and 1990-2002 using data of the exponent  $\gamma$  calculated for these periods (Fig.2). Results of calculated temporal changes of the  $\nu_y$  are presented in Fig.4ab (dashed line).

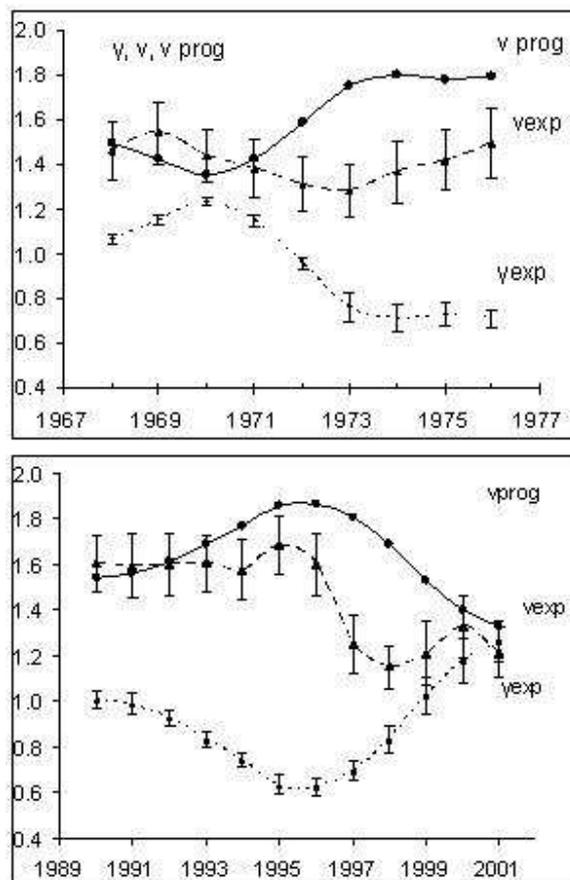


Fig. 4: Temporal changes of the  $\gamma$  and  $\nu_y$  for two time intervals, 1967-1976 (a) and 1990-2002(b).

Also, in Fig.4ab are presented temporal changes of  $\gamma$  (dot lines), and calculated  $\nu$  solid lines), in period 1967-1976 (Fig.4a), and - in period 1990-2002 (Fig.4b).

Fig.4ab show that the violence of the relationship between  $\gamma$  and  $\nu$  is observed in both cases in the minimum and near minimum epochs of solar activity, particularly in 1972-1976, and in 1996-1999. Thus, we suppose that the relationship between exponents  $\gamma$  and  $\nu$ , is almost a universal from point of view of the long period GCR intensity variations, i.e. we can successfully use the exponent  $\gamma$  as an important index, to study different classes of the GCR intensity variations, caused by the changes of IMF turbulence. Sunspots numbers  $W$  is an important index of solar activity. It shows a level of solar activity and contains some indirect information about the sizes and magnetic fields of the area occupied by sunspots, however sunspots number  $W$  could not be considered as a parameter which can be directly included in the model describing a modulation of the GCR intensity based on the transport equation.

Contrary, the exponent  $\gamma$  calculating based on the GCR experimental data has a clear physical sense; it shows a rigidity dependence of the amplitudes of the considering type of variations of the GCR intensity and can be directly included in the transport equation through diffusion coefficient, e.g., as  $K \propto R^\alpha$  ( $\gamma \propto \alpha$ ) in

the modeling of different classes of the GCR intensity variations. It is obvious that this conception is acceptable when the average global IMF turbulence is considered as an isotropic with the Gaussian distribution, and the transition energy of GCR modulation is not  $\sim 2\text{GeV}$  [6], but  $>100\text{GeV}$  [2,3,11,12,13].

### III. SUMMARY

1. We show that the rigidity spectrum of the long-period variations of the GCR intensity is hard in the minimum epochs of solar activity ( $\gamma \approx 0.6$ ) when the exponent  $\nu$  of the PSD of the IMF is higher ( $\nu \approx 1.9$ ), and is soft in the maximum epochs ( $\nu \approx 1.2$ ), when the exponent  $\nu$  is relatively lower ( $\nu \approx 1.4$ ). We ascribe these features to the essential rearrangement of the structure of the IMF turbulence in the range of frequency  $f \approx 4 \cdot 10^{-6} - 10^{-5} \text{Hz}$  during the 11-year cycle of solar activity.

2. The rigidity spectrum exponent  $\gamma$  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 ( $\sim 4 \cdot 10^{-6} - 10^{-6} \text{Hz}$ ), to which neutron monitors and ground muon telescopes are respond

### REFERENCES

- [1] Dorman, L. I. Variations of galactic cosmic rays, Moscow, p.214, in Russian, 1975
- [2] 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
- [3] Alania, M.V., K., Iskra, Siluszyk M., New index of long-term variations of galactic cosmic ray intensity *Adv. Space Res.*, 41 (2), 267-274, 2008.
- [4] <http://spidr.ngdc.noaa.gov/spidr/index.jsp>
- [5] 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
- [6] Jokipii, J.R., Propagation of cosmic rays in the solar wind, *Rev. of Geophysics and Space Physics*, 9, 27-87, 1971
- [7] Burlaga L.F., *Interplanetary Magnetohydrodynamics*, Oxford University Press, New York, 1995.
- [8] Burlaga, L. F., Lognormal and multifractal distributions of the heliospheric magnetic field, *JGR*, 106, A8, 15917-15928, 2001
- [9] Hasselman K., Winnerentz G., "Scatering of charged particles by random electromagnetic field", *Z. Gephys.*, 34, 353, 1968
- [10] Toptygin, I. N. *Cosmic rays in interplanetary magnetic fields*, D. Redel Publishing Company, Dordrecht, 1985
- [11] Wawrzynczak, A., Alania, M.V., "Peculiarities of galactic cosmic ray Forbush effects during October-November 2003", *Advanced in Space Research*, 35, 682-686, 2005
- [12] Alania, M.V. Wawrzynczak, A. "Forbush decrease of the Galactic Cosmic Ray Intensity: Experimental Study and Theoretical Modeling", *Astrophys. Space Sci. Trans.*, 4, 59-63, 2008
- [13] Ahluwalia, S. Fikani, M.M. Cosmic ray detector response to transient solar modulation: Forbush decreases, *J, Geophys. Res.* 112, A08105, 2007