On the role of the Interplanetary Magnetic Field turbulence in the change of the rigidity spectrum of Galactic Cosmic Rays during the Forbush decrease

Anna Wawrzynczak , Michael V. Alania

***Abstract*—We develop three dimensional non stationary model of the Forbush decrease (Fd) of the galactic cosmic (GCR) intensity for the constant solar wind velocity and the stationary three dimensional model including the changeable solar wind velocity and corresponding interplanetary magnetic field (IMF) components found as a solution of the Maxwell's equations. We show that the results of the theoretical modeling are in good agreement with the experimental data. Moreover, the change of the theoretical rigidity spectrum during the Fd is observed only due to the increase of the IMF turbulence, while it does not depend on the level of convection of the GCR stream. These results confirm the possibility to use the temporal changes of the rigidity spectrum exponent γ of the Fd of GCR intensity to estimate the temporal evolution of the exponent ν of the power spectral density of the IMF turbulence.**

1. Introduction

We show that [1]-[3] the changes of the rigidity R spectrum $\delta D(R)/D(R) \propto R^{-\gamma}$ of the Forbush decreases (Fd) of the galactic cosmic ray (GCR) intensity found by neutron monitors and ground muon telescopes experimental data is related with the changes of the power spectral density (PSD) of the interplanetary magnetic field (IMF) turbulence (PSD $\propto f^{-\nu}$, f is a frequency); namely the exponent γ depends on the exponent ν in the range of frequency f of the IMF turbulence, $f\sim10^{-6}$Hz - 10^{-5} Hz, to which neutron monitors and ground muon telescopes respond. A relationship between the exponent γ and the exponent ν [1]-[3] exists owing to the dependence of the diffusion coefficient K of GCR particles on the rigidity R as, $K \propto R^{\alpha}$, i.e. that the exponent γ is proportional to the α. According to the quasi linear theory (QLT), the coefficient α depends on the exponent ν of the PSD of the IMF turbulence, as $\alpha = 2-\nu$ [4]-[7]. Our aim in this paper is twofold; (1) to study the temporal changes of the rigidity spectrum and the change of the IMF turbulence during the Fd by the experimental data, and (2) to develop three dimensional (3-D) non stationary model of the Fd for the constant solar wind velocity and the stationary 3-D model for the changeable solar wind velocity including corresponding components of the IMF obtained as the solutions of the Maxwell's equation divB=0.

Anna Wawrzynczak is with the Institute of Computer Sciences of the University of Podlasie, Poland, Siedlce, (e-mail: awawrzynczak@ap.siedlce.pl)

Michael V.Alania is with the Institute of Mathematics and Physics of the University of Podlasie, Poland, Siedlce, (e-mail: alania@ap.siedlce.pl).

2. Experimental Data Analysis

For the analyze we consider the period of 24 August-10 October 2005. In Fig.1 are presented changes of the Bx, By and Bz components of the IMF (from ACE), GCR intensity by Moscow neutron monitor, DST index and solar wind speed. We study the temporal changes of the rigidity spectrum of Fd of the GCR intensity occurred in 9-25 September 2005.

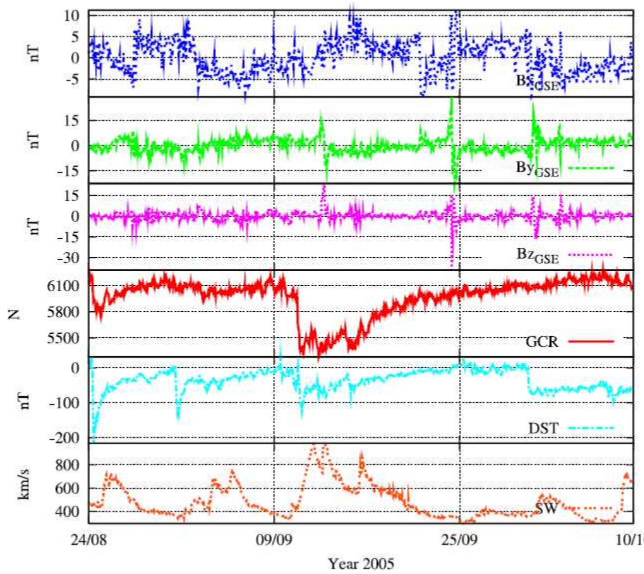

Fig.1. Changes of the Bx, By and Bz components of the IMF (from ACE), GCR intensity by Moscow neutron monitor, DST index and solar wind speed (SW) in the period of 24 August – 10 October 2005.

To study Fd we use daily average data of the neutron monitors (Apatity, Calgary, Fort Smith, Tbilisi, Thule) and different channels of Nagoya muon telescope(N0VV, N1NN, N4NW) (upper panel of Fig. 2). The exponent γ of the power law rigidity spectrum was found using the expression [9]:

$$\frac{\delta D(R)}{D(R)} = \begin{cases} A R^{-\gamma} \; for & R \le R_{max} \\ 0 \quad for & R > R_{max} \end{cases}$$

Where R_{max} is rigidity beyond which the Fd of the GCR intensity vanishes. The method of calculation is described in papers [1]-[4].

Fig. 2 (bottom panel) shows that rigidity spectrum during the beginning and recovery phases of the Fd is relatively soft with respect to the rigidity spectrum in the minimum and near minimum phases of the GCR intensity

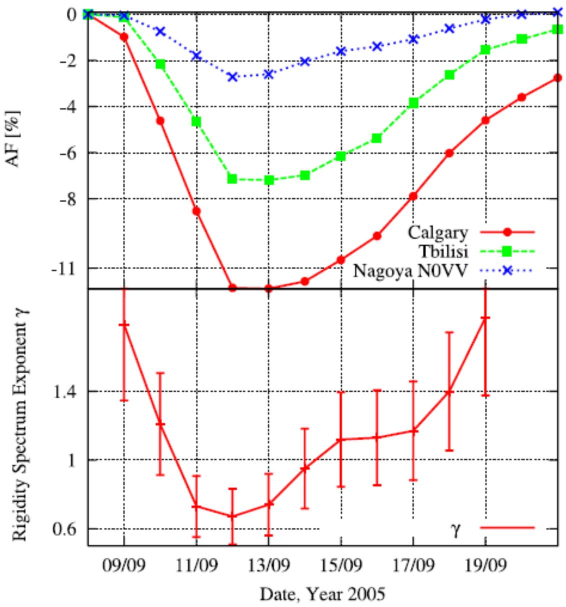

Fig. 2. Temporal changes of the GCR intensity (top panel) for Calgary and Tbilisi neutron monitors and Nagoya N0VV muon telescope and of the rigidity spectrum exponent γ (bottom panel) for period of 9-20 September 2005.

The temporal changes of the exponent γ (bottom panel of Fig.2) we ascribe to the conversion of the structure of the IMF turbulence during the Fd. Particularly, the hardening of the rigidity spectrum $\delta D(R)/D(R) \propto R^{-\gamma}$ of the Fd (the exponent γ gradually decreases in the minimum and near minimum phases of the Fd) should be 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). First of all, to carry out a study of the Fd in September 2005, we consider three periods, first one (I: 24 August – 8 September 2005) – before the Fd, the second one (II: 9-24 September 2005) –during Fd, and the third one (III: 25 September- 10 October 2005) after the Fd.

To estimate a degree of relation of γ with ν there is necessary to find ν of the PSD of the Bx, By and Bz components of the IMF with the acceptable accuracy for the relatively quiet periods before and after the Fd, and compare that with the results during the Fd (period of disturbances). Fig. 3 shows that during the Fd (II period) the exponents ν are greater for By and Bz components of the IMF, than before (I period) and after the Fd (III period). So, during the Fd is observed the inverse dependence between the changes of the exponents ν and γ; when the exponent ν increases the exponent γ decreases.

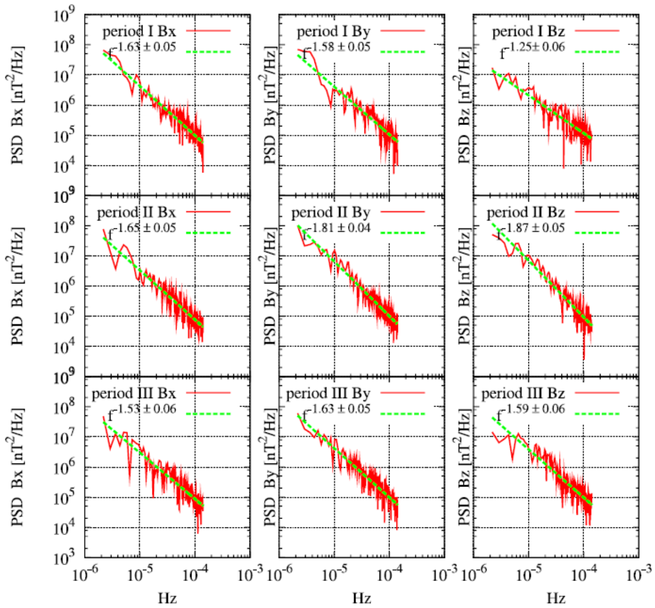

Fig. 3. Power Spectrum Density of the Bx, By and Bz components of the IMF for the periods before (I), during (II) and after (III) the Fd in September 2005.

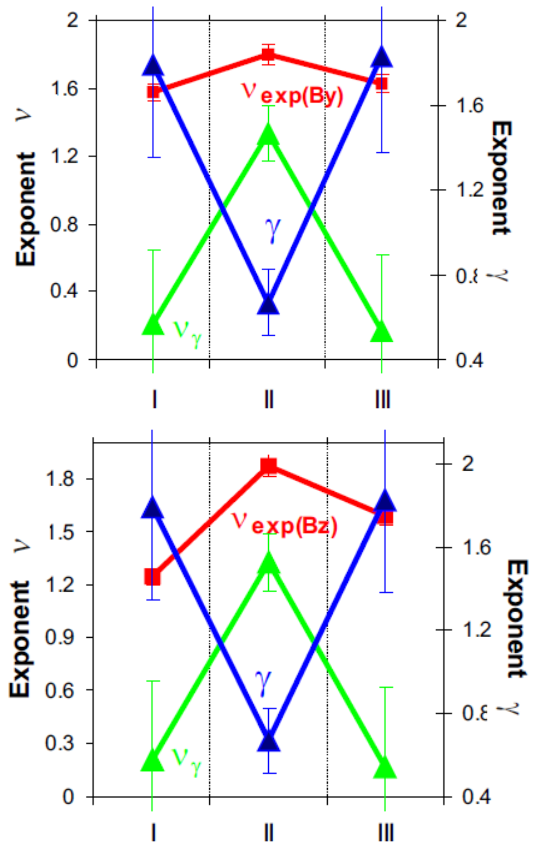

Fig. 4. Changes of the exponent γ of the rigidity spectrum (triangle), changes of the exponent ν of the PSD of the IMF turbulence (squares) calculated based on the experimental data and the changes of the exponent ν_γ predicted based on the changes of the exponent γ of the rigidity spectrum from the postulated dependence $\nu \approx 2-\gamma$ in periods before (I), after (III) and during (II) the September 2005 Fd for By and Bz component of the IMF.

In connection with this we can consider one backward problem; namely, use the temporal changes of the rigidity spectrum exponent γ of the Fd of GCR intensity to estimate the evolution of the IMF's turbulence (Fig.4). In the Fig.4 are presented results for two B_y and B_z components of the IMF. The 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.

2. Model of the Forbush Decrease

To describe the Fd of the GCR we use the Parker's transport equation [10]

$$\frac{\partial N}{\partial t} = \nabla_i \left(K_{ij} \nabla_j N\right) - \nabla_i \left(U_i N\right) + \frac{1}{3} \frac{\partial}{\partial R}(N R) \nabla_i U_i \qquad (1)$$

Where N and R are density and rigidity of cosmic ray particles, respectively; U_i – solar wind velocity, K_{ij} -is the anisotropic diffusion tensor of cosmic rays, which for the three dimensional IMF has the form [11], [12]:

$$K_{rr} = K_{II}\left[\cos\delta^2 \cos\psi^2 + \beta\left(\cos\delta^2 \sin\psi^2 + \sin\delta^2\right)\right]$$
$$K_{r\theta} = K_{II}\left[\sin\delta \cos\delta \cos\psi^2 (1-\beta) \mp \beta_1 \sin\psi\right]$$
$$K_{r\varphi} = K_{II}\left[\sin\psi \cos\delta \cos\psi (\beta - 1) \mp \beta_1 \sin\delta \cos\psi\right]$$
$$K_{\theta r} = K_{II}\left[\sin\delta \cos\delta \cos^2\psi (1-\beta) \pm \beta_1 \sin\psi\right]$$
$$K_{\theta\theta} = K_{II}\left[\sin^2\delta \cos^2\psi + \beta\left(\sin^2\delta \sin^2\psi + \cos^2\delta\right)\right]$$
$$K_{\theta\varphi} = K_{II}\left[\sin\delta \sin\psi \cos\psi (\beta - 1) \pm \beta_1 \cos\delta \cos\psi\right]$$
$$K_{\varphi r} = K_{II}\left[\cos\delta \sin\psi \cos\psi (\beta - 1) \pm \beta_1 \sin\delta \cos\psi\right]$$
$$K_{\varphi\theta} = K_{II}\left[\sin\delta \sin\psi \cos\psi (\beta - 1) \mp \beta_1 \cos\delta \cos\psi\right]$$
$$K_{\varphi\varphi} = K_{II}\left[\sin^2\psi + \beta \cos^2\psi\right]$$

Where δ is the angle between the lines of the IMF and the radial direction in the meridian plane ($\delta = \arctan(B_\vartheta / B_r)$ and $\psi = \arctan(-B_\varphi / B_r)$ for A>0 solar magnetic cycle in the spherical coordinate system r,ϑ, φ; β and β_1 are the ratios of the perpendicular $K_\perp$ and drift K_d diffusion coefficients to parallel K_{II} diffusion coefficient with respect to the regular IMF lines ($\beta = K_\perp / K_{||}$ and $\beta_1 = K_d / K_{||}$), respectively.

Our aim is to show theoretically a dependence of the expected rigidity spectrum exponent γ of the Fds on the exponent ν of the PSD of the IMF turbulence. It should be observed (according to our thesis), as far there exists a dependence of diffusion coefficient K on the GCR particles rigidity R as, $K \propto R^\alpha$, i.e. when the QLT is valid (for the rigidity of GCR particles registered by neutron monitors and muon telescopes).

A. *Non stationary model of the Fd*

In the non stationary models the diffusion coefficient $K_{II} = K_0\, K(r)\, K(R,t)$, were $K_0 = 4.5 \times 10^{21}\ cm^2/s$, $K(r) = 1 + 0.5\left(\frac{r}{1AU}\right)$; here *r* is heliocentric distance, *t*-time. To show the dependence of the exponent γ on the exponent ν, we assume the change of the diffusion coefficient on ν, as $K(R,t) = R^{\alpha(t)} = R^{2-\nu(t)}$. The exponent ν in the vicinity responsible for the Fd changes, as $\nu(t) = 0.8 + 35 * \left(\frac{3t - 0.3}{3}\right)^{1.5} * Exp(-8*(t-0.1))$ (Fig. 6).

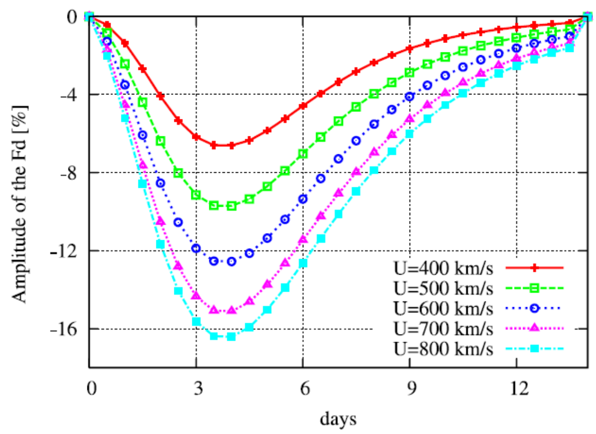

Fig.5. Changes of the expected amplitudes of the Fd of the GCR intensity for the rigidity of 10 GV based on the solutions of the model of the Fd for different solar wind velocities.

Method of solution of the non stationary (1) is presented in [13]. We solve (1) for different constant in time solar wind velocities, U= 400, 500, 600, 700 and 800 km/s in order to show that γ does not depend on the level of convection of the GCR stream, but depends generally only on the state of the turbulence of the IMF.

Changes of the relative density obtained as a solution of the transport equation for different solar wind velocities (U= 400, 500, 600, 700 and 800 km/s) and the calculated expected power law $R^{-\gamma}$ rigidity spectrum exponents γ of the Fd are presented in Fig. 5 and Fig 6, respectively. We see that with the increase of the solar wind velocity we observe the increase of the amplitudes of the simulated Fd (Fig.5). In doing so, the similar changes of the rigidity spectra with the inverse dependence between the changes of the exponent γ and the exponent ν are observed for all considered models (Fig.6). It is in agreement with our thesis anticipating a change of the rigidity spectrum of Fd only versus the changes of the exponent *ν*.

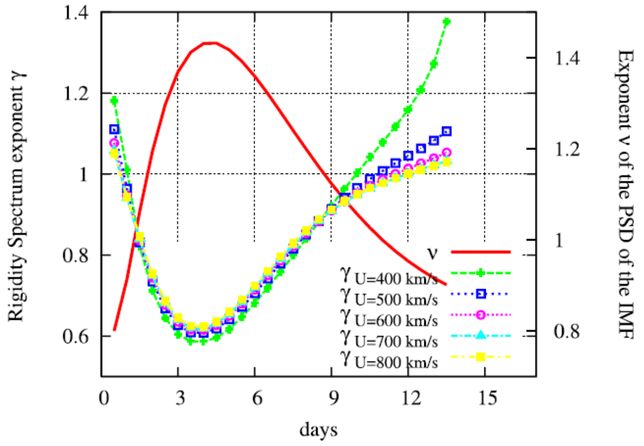

Fig. 6. Temporal changes of the expected rigidity spectrum exponent γ and exponent ν of the PSD of the IMF turbulence for model of the Fd.

B. *Stationary model of the Fd*

An applying of the stationary model to describe the Fd is justified, while the amplitudes of the Fd of GCR intensity generally are rather small (≤ 5-6% in the energy range of 10 GeV) and duration is reasonably large (10-12 days). In case of the stationary models as the model of the Fd we consider the changes of the expected density versus the heliolongitudes (the value of the heliolongitudes 13.3^{o} corresponds to the 1 day).

To investigate in detail the Fd there is necessary to take into account the increase of the solar wind velocity during the main phase of the Fd.

Inclusion in the model the change of the solar wind velocity and three dimensional IMF (B_r, B_θ, and B_φ components) depending on the spatial coordinates requires to investigate a conservation of divergence free IMF. The equation divB=0 (B is the strength of the IMF) for the azimuthally depending of the radial component of the solar wind velocity (Fig.7) is solved in [8]. The assumed solar wind velocity, and B_r , B_φ components of the IMF obtained as solutions of the equation divB=0 are presented in Figs. 7-9, respectively.

In contrast to our assumption in section A, we suppose that the exponent ν in the vicinity responsible for the Fd changes as: $\nu(\varphi) = 0.8 + 0.5 * (\cos(\varphi) + 0.2)$ (Fig. 11). At the same time we assume the changes of the solar wind velocity, as $U(\varphi,\theta) = 400 * \left(1 + \delta * \left(-\exp(-0.7\varphi + 80^\circ) * \cos(1.1\varphi) + 0.1\right) * \left(0.2 + \sin\theta\right)\right)$, where the maximal velocity is changing by expense of the coefficient $\delta = \{1, 0.75, 0.5, 0.25, 0.1\}$ from 480 to 780 km/s. (Fig. 7).

Changes of the relative density obtained as a solution of the (1) for various profiles of the solar wind velocity (Fig. 7) and the calculated expected power law $R^{-\gamma}$ rigidity spectrum exponents γ of the Fd are presented in Fig. 10 and Fig 11, respectively. We see that the various levels of the solar the wind velocity, e.g. an increase of it, causes a increase of the amplitudes of the simulated Fds (Fig. 10), but without any influence on the changes of the rigidity spectrum exponent γ, as it is seen from Fig. 11. This effect also confirms our assumption that a change of the rigidity spectrum of Fd is observed only versus the changes of the exponent ν.

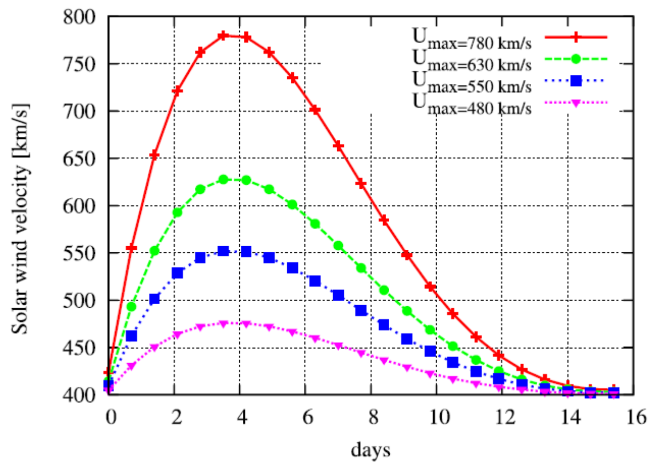

Fig. 7. Changes of the solar wind velocities during the Fd included in the stationary model of the Fd.

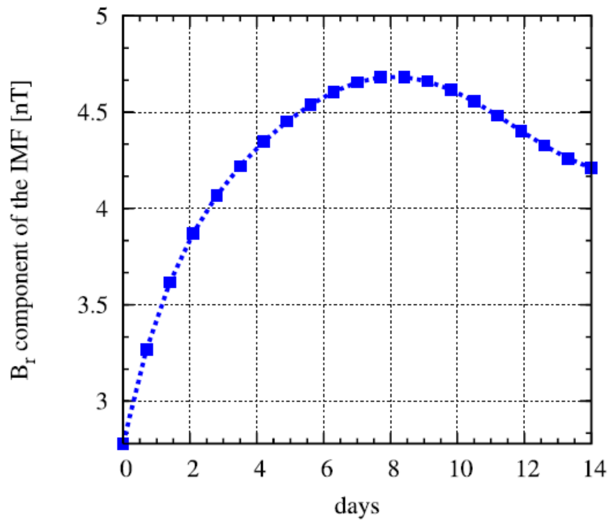

Fig.8. Azimuthal changes of the B_r component of the IMF at the Earth orbit during the Fd.

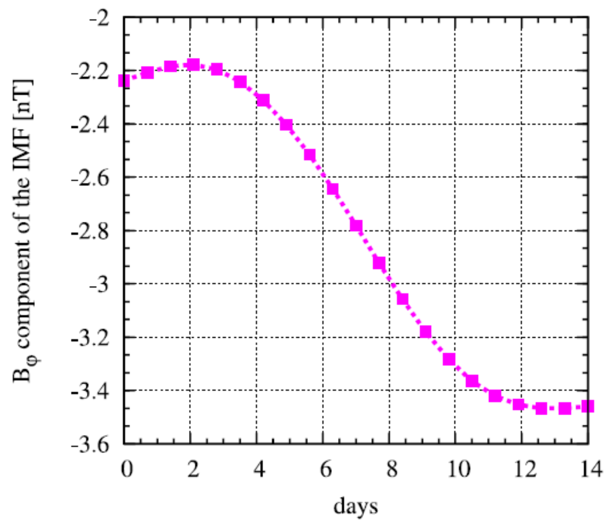

Fig. 9. Azimuthal changes of the B_φ component of the IMF at the Earth orbit during the Fd.

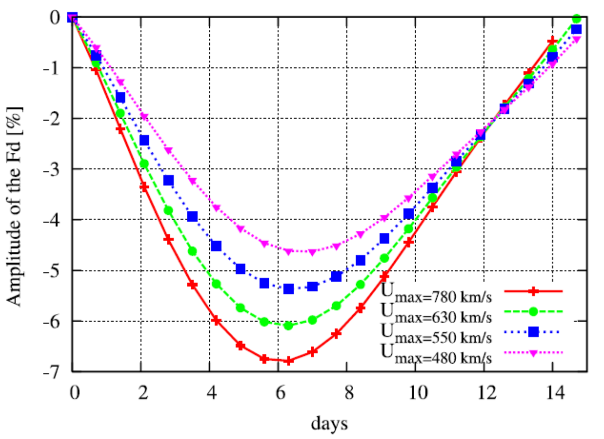

Fig. 10. Changes of the expected amplitudes of the Fd of the GCR intensity for the rigidity of 10 GV based on the solutions of the stationary model of the Fd for changeable solar wind velocities

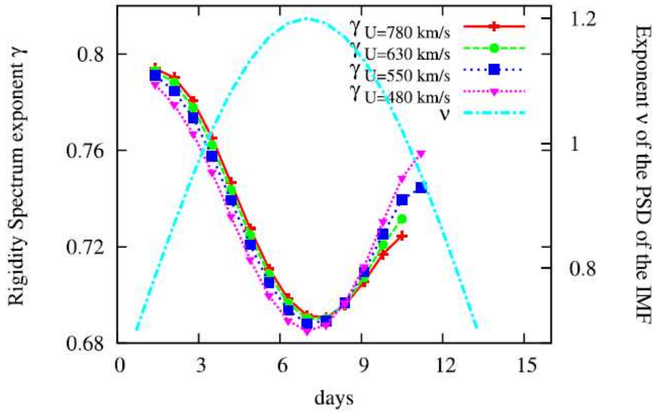

Fig. 11. Temporal changes of the expected rigidity spectrum exponent γ and exponent ν of the PSD of the IMF turbulence for the models of the Fd with changeable solar wind velocity.

3. Conclusion

1. The hardening of the rigidity spectrum $\frac{\delta D(R)}{D(R)} \propto R^{-\gamma}$ of the Fd of the GCR intensity (the exponent γ gradually decreases) in the minimum phase of the Fd takes place owing to the increase of the exponent ν of the PSD of the IMF turbulence caused by the creation of the new, relatively large scale irregularities in the $10^{-6}\,Hz \div 10^{-5}\,Hz$ range of IMF turbulence. This process can be taken place due to the non linear interactions of the high speed solar wind streams with the background solar wind.
2. The relationship between the exponent γ and the exponent ν is observed owing to the dependence of the diffusion coefficient K of GCR particles on the rigidity R as, $K \propto R^{\alpha}$ where, according to the quasi linear theory $\alpha = 2 - \nu$ (for $R \geq 1GV$).
3. The temporal changes of the rigidity spectrum exponent γ of the Fd of GCR intensity can be successfully used to estimate the temporal evolution of the IMF turbulence for the arbitrary period (sufficient for calculation of γ), which is not achievable by the in situ measurements of the IMF.
4. The proposed models (stationary and non stationary) reasonably describe the behavior of the exponent γ during the Fd; the theoretical calculations are compatible with the results obtained based on the neutron monitors and ground muon telescopes experimental data and confirms theoretically a dependence of the expected rigidity spectrum exponent γ of the Fds on the exponent ν of the PSD of the IMF turbulence; at the same time γ does not depend on the level of convection of the GCR stream.

Acknowledgments

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