

# The connection of the interplanetary magnetic field turbulence and rigidity spectrum of Forbush decrease of the galactic cosmic ray intensity

A. Wawrzynczak<sup>1</sup>, M.V. Alania<sup>2</sup>

<sup>1</sup>Institute of Computer Sciences, Siedlce University, Poland,

<sup>2</sup>Institute of Mathematics and Physics, Siedlce University, Poland .

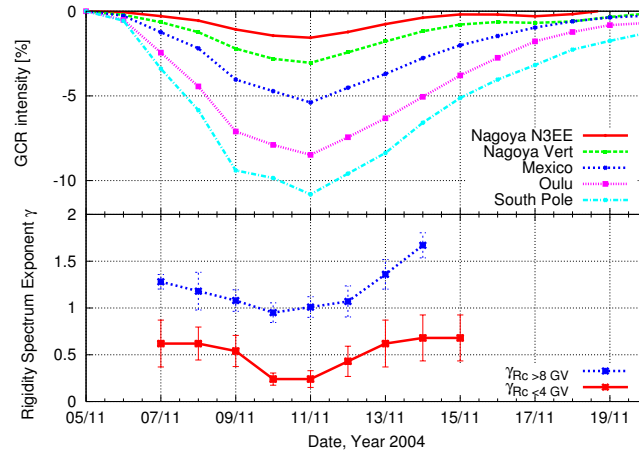
E-mail: awawrzynczak@uph.edu.pl, alania@uph.edu.pl

**Abstract.** We analyze the temporal changes in the rigidity spectrum of Forbush decrease (Fd) of the galactic cosmic ray (GCR) intensity observed in November 2004. We compute the rigidity spectrum in two energy ranges based on the daily data from the worldwide network of neutron monitors and Nagoya ground muon telescope. We demonstrate that the changes in the rigidity spectrum of Fd are linked to the evolution/decay of the interplanetary magnetic field (IMF) turbulence during various phases of the Fd. We analyze the time-evolution of the state of the turbulence of the IMF in various frequency ranges during the Fd. Performed analysis show that the decrease of the exponent  $\nu$  of the Power Spectral Density ( $PSD \propto f^{-\nu}$ , where  $f$  is frequency) of the IMF turbulence with decreasing frequency lead to the soft rigidity spectrum of Fd for GCR particles with relatively higher energies.

## 1. Introduction

A fast decrease of the galactic cosmic ray (GCR) intensity during one-two days followed by its gradual recovery is called a Forbush decrease (Fd) [1]. Forbush decreases (Fds) are formed after outstanding flares on the Sun and intensive solar coronal mass ejecta (CME) [2, 3]. These features appear randomly without any regularity, increasing its frequency in declining phase of a solar sunspot cycle. Cane [3] divided Fds into three basic types: (1) caused by a shock and ejecta, (2) caused by a shock only, and (3) caused by the ejecta only. The amplitude of the Fd is defined as the difference between the GCR intensity at the onset and the minimum point of the Fd. A dependence of the Fd amplitude on the rigidity of GCR particles is one of its essential characteristics, called the rigidity spectrum of the Fd. Lots of papers are devoted to this problem. Cane [3] notes that, if the power law  $R^{-\gamma}$  gives the rigidity dependence of the amplitude of the Fds, then  $\gamma$  ranges from about 0.4 up to 1.2. In [4] authors described a new methodology for the study of the rigidity dependence of the transient modulations with use of median rigidity of response of a detector. Their results confirm the power law rigidity dependence of the Fds amplitudes with the negative exponents [5]. In [6] was studied a dependence of the recovery time of Fd on the energy of cosmic rays. Authors found that Fds with magnitudes exceeding 10% show an energy dependence of the recovery time while Fds with lesser amplitudes show no energy dependence. We are confident that an examination of the rigidity dependence of Fd only through the amplitudes for one point of the GCR intensity minimum is not sufficient. So, we consider to study dynamics of the Fd as a vital to establish a





**Figure 1.** *Top panel:* Three day averaged temporal changes of the GCR intensity for the Mexico, Oulu and South Pole neutron monitors and Vertical and N3EE channels of Nagoya muon telescope during the Fd. *Bottom panel:* Temporal changes in the rigidity spectrum exponent  $\gamma$  based on the data of the stations divided into two groups according to their cut-off rigidities.

rigidity dependence of the GCR intensity in different phases of the Fd. This type of study was presented in [7, 8, 9, 10, 11] and references therein. In these papers it has been shown that a rigidity spectrum  $\delta D(R)/D(R) \propto R^{-\gamma}$  of the vast majority of the Fds gradually hardens during the decreasing and minimum phases of the Fd and gradually softens in the recovery phase of the Fd. So, the exponent  $\gamma$  of the rigidity spectrum of the Fd is in the range  $\gamma \in [1, 1.6]$  at the beginning phase of the Fd, then it gradually decreases up to the minimum (or near minimum) of the GCR intensity, when it takes the lowest value  $\gamma \in [0.2, 0.6]$  and increase again during the recovery phase of the Fd. Moreover, the time profiles of the Fds rigidity spectrum are associated with the changes of the power spectral density (PSD) of the interplanetary magnetic field (IMF) turbulence ( $PSD = P(\frac{f}{f_0})^{-\nu}$ , where  $P$  is power,  $f$  is frequency and  $f_0$  is normalization frequency) [7, 8, 9, 10, 11]. Specifically, changes in the exponent  $\gamma$  of the power law rigidity  $R$  spectrum explicitly depends on the changes of the exponent  $\nu$  of the PSD in the range of frequency  $f \in [10^{-6}, 10^{-5}]$  Hz of the IMF turbulence, to which neutron monitors and ground muon telescopes respond. This relation can be deduced based on the dependence of the diffusion coefficient  $K_{II}$  of GCR particles on the rigidity  $R$ , as  $K \propto R^{2-\nu}$ , where  $\nu$  is exponent of the PSD of the IMF turbulence e.g.[12, 13, 14].

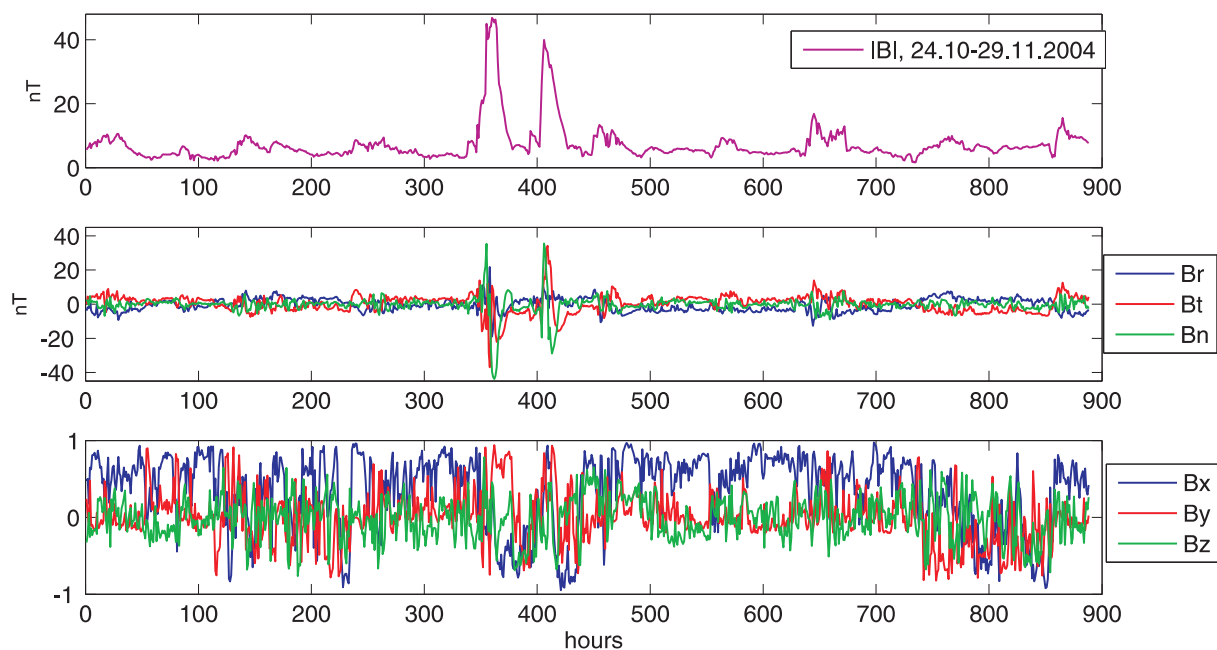
The relation between the exponents  $\gamma$  and  $\nu$  entails expectation of the rigidity dependence of the exponent  $\gamma$  arising from the changes in the exponent  $\nu$  versus frequency. However, to reveal the rigidity dependence of  $\gamma$  it is a difficult task for Fd due to its complexity. In [8] it was presented that during the Fd in September 9-23, 2005 is observed clearly recognized dependence of the exponent  $\gamma$  of the rigidity spectrum of the Fd on the rigidity of GCR particles, when the exponent  $\gamma$  is larger, the larger are the cut-off rigidities of stations used in its calculations; i.e. the rigidity spectrum of the GCR intensity variations during the Fd is hard for lower energy range and is soft for the higher energy range. Correspondingly, the consistent frequency dependence of the exponent  $\nu$  of the PSD of the IMF components during the Fd was observed.

In this paper, we reinforce the existence of the rigidity dependence of the exponent  $\gamma$  during the Fd by the detailed examination of the Fd in November 2004. We also evaluate the temporal

evolution of the state of the turbulence during the Fd by the calculation of the PSD of the running series of IMF components. The gradual increase of the exponent  $\nu$  during the Fd is clearly manifested. Moreover, we show that the decrease of the exponent  $\nu$  with decreasing frequency lead to the soft rigidity spectrum of the Fd for GCR particles with higher rigidities.

## 2. Experimental data and methods

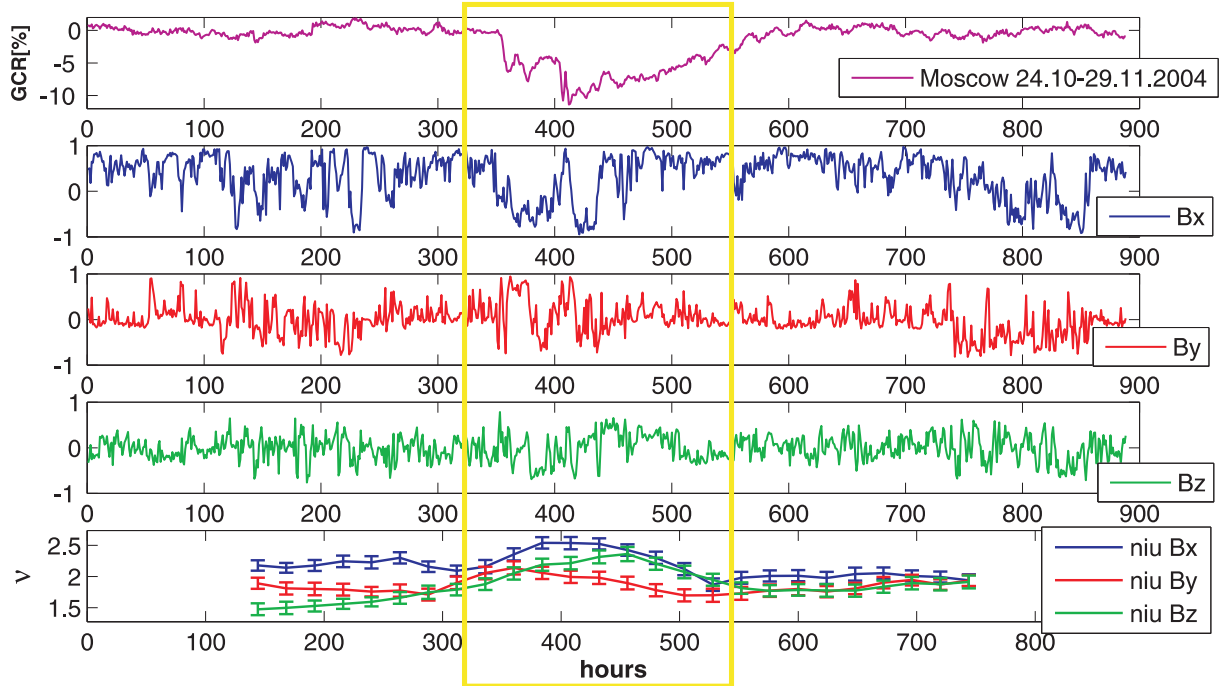
The Sun's activity in November 2004 revealed a series of consecutive CMEs appearing from 4 to November, 10. They were the result of solar flares in the active region of the Sun marked as 10696. The first class C6 flare occurred on November 6, the outcome was a halo CME, which reached the Earth on November 7. According to NOAA, in the following days the halo or part-halo CMEs appeared almost daily [15]. The result was 2-3 shock waves spreading at the same time. The strongest X2.8 solar flare occurred on November, 10 and reached the Earth on November 12 in the form of CME. The highest solar wind speed was 700-800 km/s and the magnetic field strength 45 nT. The result of this activity was a Fd of the GCR intensity observed at the Earth by neutron monitors and ground muon telescopes in the period of November 5-20, 2004.



**Figure 2.** The IMF strength (top panel) and its components in the RTN (middle panel) [18] and in the mean field (bottom panel) coordinate system for the period of October 24 - November 29, 2004.

### 2.1. Rigidity spectrum of the Fd

The rigidity spectrum of the Fd in November 5-20, 2004 was earlier examined in [7]. We have revealed that the rigidity spectrum of this Fd is soft at the beginning of the Fd ( $\gamma \approx 1.15 \pm 0.3$ ), then it slowly becomes hard during the declining and minimum phases of the Fd ( $\gamma \approx 0.7 \pm 0.15$ ) and gradually becomes soft ( $\gamma \approx 1.35 \pm 0.32$ ) in the recovery phase. Currently, we investigate whether we observe the rigidity dependence of the rigidity spectrum exponent  $\gamma$  for this Fd. For this purpose, we calculate the rigidity spectrum of the Fd based on the GCR intensity from



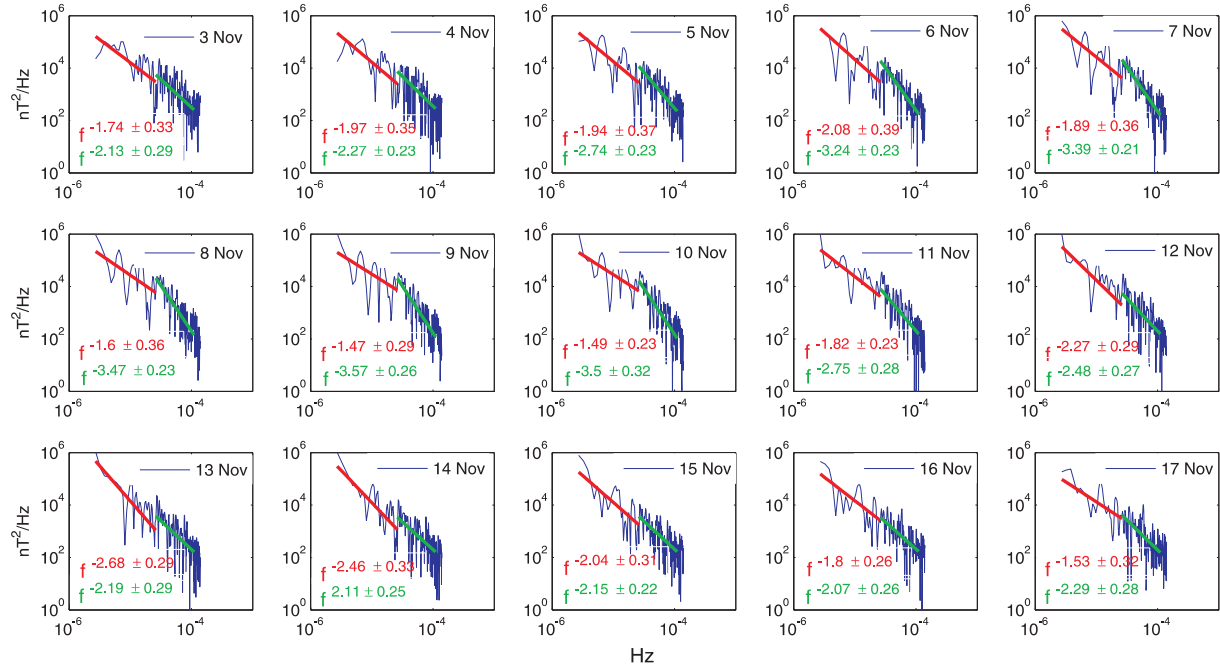
**Figure 3.** The hourly changes of the GCR intensity measured by the Moscow neutron monitor, IMF components in the mean field coordinate system and the values of the exponent  $\nu$  of the PSD for IMF components based on the 12 days running series of hourly IMF data in October 24 - November 29, 2004.

neutron monitors and the Nagoya ground muon telescope data divided into two groups according to their cut-off rigidities: for low and high cut-off rigidities. In the group of stations with low ( $R_c < 4GV$ ) cut-off rigidities were stations: Calgary, Cape Smidth, Kergelungen, McMurdo, Oulu, South Pole, whereas in the group of station with high cut-off ( $R_c > 8GV$ ) rigidities were: Haleakala, Mexico and following channels of Nagoya muon telescope: N0VV, N1EE, N3EE, N4NE, N4SE.

The top panel in Fig. 1 presents changes in the GCR intensity smoothed over three days measured by Mexico, Oulu and South Pole neutron monitors, and N3EE channel of Nagoya ground muon telescope. We consider smoothed data in order to reveal reliable average temporal changes in the rigidity spectrum exponent  $\gamma$  and its energy dependence. The rigidity spectrum exponent  $\gamma$  of the power law rigidity spectrum was found using the expression e.g. [16, 17]:

$$\frac{\delta D(R)}{D(R)} = \begin{cases} AR^{-\gamma} & R \leq R_{max} \\ 0 & R > R_{max}, \end{cases} \quad (1)$$

$R_{max}$  designates the upper limiting rigidity beyond which the Fd of the GCR intensity disappears (200 GV). The daily average amplitudes  $J_i^k$  of the Fd for the 'i-th' detector (neutron monitor or muon telescope) were calculated, as:  $J_i^k = (N_k - N_0)/N_0$ ;  $N_k$  is the running daily average count rate ( $k=1,2,3,...,days$ ) and  $N_0$  is the 3 days average count rate before the Fd (3-5 November). Based on the method in detail described in [8] we calculated the rigidity spectrum exponent  $\gamma$  of Fd for each day of November 5-20, 2004. The bottom panel in Fig. 1 presents temporal changes in rigidity spectrum exponent  $\gamma$  ( $k=1,2,3,...,days$ ). The exponent  $\gamma$  was calculated for two groups of stations with  $R_c < 4GV$  and  $R_c > 8GV$ . Fig. 1 shows that time profile of  $\gamma$  is approximately the same for both cut-off rigidity groups. However, the values of  $\gamma$  are larger for the group with higher



**Figure 4.** The PSD for the IMF component  $Bz$  based on the 12 days running series of hourly data in November 2004.

cut-off rigidities. The value of  $\gamma_{R_c > 8GV}$  changes from  $\gamma_{R_c > 8GV} = 1.28 \pm 0.08$  at the beginning of the Fd down to  $\gamma_{R_c > 8GV} = 0.95 \pm 0.1$  in the minimum of the Fd, and increases again in the recovery phase up to  $\gamma_{R_c > 8GV} = 1.67 \pm 0.13$ . In turn, the exponent  $\gamma_{R_c < 4GV}$  estimated based on the low cut-off stations data is smaller by factor of 0.6, changing from  $\gamma_{R_c < 4GV} = 0.62 \pm 0.25$ , through  $\gamma_{R_c < 4GV} = 0.24 \pm 0.19$  up to  $\gamma_{R_c < 4GV} = 0.68 \pm 0.24$ . Consequently, we can conclude that rigidity spectrum of Fd is hard for the lower energy range and is soft for the upper energy range. This conclusion is in agreement with results obtained in [8] for Fd in September 2005.

## 2.2. Power spectral density of the IMF during Fd

Hitherto in [7, 8, 9, 10] was presented that during the Fd we observe an increase of the exponent  $\nu$  of the PSD of the IMF components. However, it was done based on the comparison of the single data series with the length predetermined by the duration of the Fd; i.e. the PSDs were calculated for three periods, before, during and after the Fd. This results from the requirement of employing relatively long data series to attain the values of the exponent  $\nu$  in low frequency range ( $f \in [10^{-6}, 10^{-5}]$ ) responsible for the scattering of the GCR particles to which neutron monitor and ground meson telescopes respond. In this paper, we analyze the time-evolution of the state of the turbulence of the IMF when approaching the Fd. In the calculations, we used the hourly data of the IMF components recorded by the ACE spacecraft [18] for the period of October 20, 2004 - November 29, 2004 (Fig. 2). Before the calculation of the PSD of the IMF components, we convert the IMF from RTN to the mean field reference system [19]. The mean field reference system reduces the problem of cross-talking between the components, because the interplanetary magnetic field is not oriented along the axes of the reference system in which spacecraft perform the measurement. In consequence, any component will experience a contribution from the other ones. Fig. 2 presents the hourly changes in the IMF components in the RTN and the mean field reference system in the considered period. The mean field reference system is oriented as follows: the direction  $Bx$  is parallel to the mean field direction,  $Bz$  is

perpendicular to  $Bx$  and radial direction and the  $By$  completes the system.

To estimate the PSD of the IMF turbulence in the frequency range responsible for the modulation of the GCR particles registered by neutron monitors and muon telescopes we use the 12-day long series of the 1-hour data (288 hours). As a result, we obtain one value of  $\nu$  for each IMF component. To note the time changes of the exponent  $\nu$  we estimated the PSD for 12 days running series of data shifted by 24-hours. The results of these calculations are presented in Fig. 3. The top panel in the Fig. 3 gives the corresponding changes of the GCR intensity registered by the Moscow neutron monitor, the three following panels provide the IMF components used in these calculations. The bottom panel in Fig. 3 presents the obtained values of the exponent  $\nu$  of the PSD ( $PSD \propto f^{-\nu}$ ). We assigned value of  $\nu$  in the middle of the data series used in its calculation. One can see the gradual increase in the exponent  $\nu$  for all IMF components when we approach the period of the Fd (marked in Fig. 3 by yellow box), and then its gradual decrease when Fd is over. We can also observe some discrepancy between the time profile of  $\nu$  for  $Bx$ ,  $By$  and  $Bz$  components. This divergence suggests that the structure of the IMF turbulence was inhomogeneous and was developing differently in parallel and perpendicular directions.

Detailed analysis of bottom panel of Fig. 3 shows that the real structure of the turbulence of the IMF during the Fd can be considered as a 3-D, being a strongly anisotropic and inhomogeneous. However, if it is the case describing a scattering of the GCR particles by the slab/2-D approximation of the IMF turbulence scarcely can be valid [21]. We assume that during the Fd the 3-D turbulence of the IMF is stipulated by fluctuations of the Alfvénic waves in all three spatial directions. The  $Bx$  and  $By$  components are represented by both- regular and fluctuating parts of the IMF, while  $Bz$  component involves only fluctuations. Owing to this, in the  $\vec{z}$  direction the turbulence of the IMF is completely realized by  $Bz$  component. During the Fd the enhanced  $Bz$  component is a source of a high-level turbulence with preferentially existing the large inhomogeneities (i.e. when the exponent  $\nu$  is high).

We have also estimated the slope of the PSD of the  $Bz$  component in two frequency intervals, the first - I- $[2.7 \times 10^{-6} Hz, 5 \times 10^{-5} Hz]$ , and the second one II- $[5 \times 10^{-5} Hz, 10^{-4} Hz]$ . Fig. 4 presents that during the main phase of the Fd (6-13 November) we observe the significant increase of the slope in the higher frequency range.

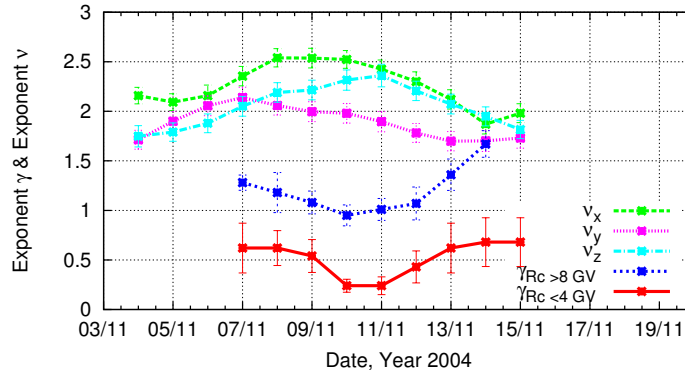
### 2.3. Relationship between the exponents $\gamma$ and $\nu$ during the Fd

The comparison of the time profiles of the rigidity spectrum of the Fd exponent  $\gamma$  and the exponent  $\nu$  of the PSD of the IMF components during the Fd in November 2004 is presented in Fig. 5. Fig. 5 confirms that during the Fd in November 2004 we observe a gradual decrease of the exponent  $\gamma$  simultaneously with the progressive increase of the exponent  $\nu$ , and then its return to the initial level. The correlation coefficient between all variables are presented in Table 1. The various values of correlation for the IMF's components suggests that during this Fd the IMF turbulence was propagating inhomogeneously in space. However, in this case the strongest anticorrelation is recognized for the exponent  $\nu$  for  $Bz$  component of the IMF, the weakest for the  $By$  component.

**Table 1.** Correlation coefficient between the changes of the exponent  $\gamma$  and  $\nu$  during Fd in November 4-15, 2004.

Correlation Coefficient	$\nu_{Bx}$	$\nu_{By}$	$\nu_{Bz}$
$\gamma_{R_c > 8GV}$	$-0.88 \pm 0.02$	$-0.46 \pm 0.23$	$-0.94 \pm 0.01$
$\gamma_{R_c < 4GV}$	$-0.57 \pm 0.16$	$-0.21 \pm 0.32$	$-0.85 \pm 0.03$





**Figure 5.** Temporal changes in the exponent  $\gamma$  and  $\nu$  during Fd in November 4-15, 2004.

The robust relation between the exponents  $\gamma$  and  $\nu$  is also confirmed by changes of the exponent  $\nu$  versus frequency presented in Fig. 4. Taking into account the average, for the considered period, solar wind velocity  $V = 600$  km/s and the IMF magnitude  $B = 5 \times 10^{-5}$  Gs the lower frequency range I is responsible for modulation of the GCR particles with rigidities in the range  $[10GV, 60GV]$  and higher frequency range II for modulation of the GCR particles with rigidities in  $[5GV, 15GV]$  [20]. Thus, in the lower frequency range in which GCR particles with higher energies are modulated we have smaller exponent  $\nu$ , than in the upper frequency range in which are modulated lower energy particles. This is in coincidence with the energy dependence of the exponent  $\gamma$  of the rigidity spectrum (Fig. 1); i.e. the growth of the exponent  $\gamma$  for higher energy GCR particles. This evident anticorrelation reflect the role of the exponent  $\nu$  of the PSD of the IMF in creating the dependence of the amplitudes of Fd on rigidity of GCR particles, i.e. a manifestation of the role of  $\nu$  in the formation of the rigidity spectrum (changes in  $\gamma$ ).

The proved relationship between exponents  $\gamma$  and  $\nu$  was found from the expectation that the diffusion coefficient  $K_{II}$  of GCR particles depends on the rigidity  $R$ , as  $K \propto R^{2-\nu}$ , according to QLT e.g.[12, 13, 14]. Furthermore, the dependence of the parallel diffusion coefficient  $K_{II}$  on  $\nu$  entails a dependence of the perpendicular diffusion coefficient  $K_{\perp}$  on  $R$ , as far  $K_{\perp}$  is proportional to  $K_{II}$ :  $\frac{K_{\perp}}{K_{II}} = \frac{1}{1+(\omega\tau)^2}$ , where  $\omega$  is particle angular velocity and  $\tau$  is the time between two sequence GCR particles collisions. For the GCR particles to which neutron monitor respond the  $\omega\tau$  can change in the range  $3 \leq \omega\tau \leq 5$ . In case of a more complicated expression for  $\omega\tau$  one can infer that the character of  $K_{II}$  is hidden in the  $K_{\perp}$ .

### 3. Conclusion

- (i) We presented an apparent dependence of the exponent  $\gamma$  of the rigidity spectrum of the Fd in November 2004 versus the GCR particles energy. The rigidity spectrum exponent  $\gamma$  is the larger, the higher are cut-off rigidities of stations used in calculations.
- (ii) We estimated the daily time evolution of the exponent  $\nu$  of the PSD of the IMF components throughout the Fd. Results show the gradual increase of the exponent  $\nu$  up to the main phase of the Fd and then its gradual return to the initial level.
- (iii) We have confirmed the clear anticorrelation between the exponents  $\gamma$  and  $\nu$  during the Fd.
- (iv) The presented dependence of the exponent  $\nu$  of the PSD of the IMF turbulence upon frequency during the Fd strengthen the relationship between the rigidity spectrum exponent  $\gamma$  and the exponent  $\nu$ .

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## References

- [1] Forbush S.E. 1937 *Phys. Rev.*, **51** , 11081109
- [2] Burlaga L.F. 1995 *Interplanetary Magnetohydrodynamics*, (New York: Oxford Univ. Press)
- [3] Cane H.V. 2000 *Space Sci. Rev.*, **93**, 5577
- [4] Ahluwalia H.S. and M. M. Fikani 2007 *J. Geophys. Res.*, **112** , A08105
- [5] Ahluwalia H.S., R.C. Ygbuhay and M.L. Duldig 2009 *Adv. Space Res.* ,**44**, 58-63
- [6] Usoskin I.G., Braun I. and Gladysheva O.G. et al. 2008 *J. Geophys. Res.*, **113** , A7
- [7] Alania M.V. and Wawrzynczak A. 2008 *Astrophys. And Space Sci. Transactions*, **4** , 59-63
- [8] Alania M.V. and A. Wawrzynczak 2012 *Adv. in Space Res.* **50** 725-730
- [9] Wawrzynczak A. and Alania, M.V. 2008 *Adv. in Space Res.* **41** 2, 325-334
- [10] Wawrzynczak A. and Alania M.V. 2010 *Adv. Space Res.*, **45**, 5, 622-631
- [11] Alania M.V., A. Wawrzynczak, V. E. Sdobnov and M. V. Kravtsova 2013 *Solar Phys.* **286** 561-576
- [12] Jokipii J.R. 1966 *Astrophys. J.*, **146**, 480-487
- [13] Toptygin I.N. 1985 *Cosmic rays in interplanetary magnetic fields*, (Reidel Publishing Company)
- [14] Shalchi A. 2009 *Nonlinear Cosmic Ray Diffusion Theories*, (Springer)
- [15] [http : //www.solen.info/solar/old\\_reports/2004/november/20041107.html](http://www.solen.info/solar/old_reports/2004/november/20041107.html)
- [16] Ahluwalia H.S. and J.H. Ericksen 1971 *J. Geophys. Res.*, **76** 6613-6623
- [17] Dorman L.I. 2004 *Cosmic Rays in the Earth's Atmosphere and Underground*, (Dordrecht: Kluwer Academic Publishers)
- [18] <http://www.srl.caltech.edu/ACE/ASC/level2/index.html>
- [19] Bruno R and V. Carbone 2013 *Living Rev. Solar Phys* **10**
- [20] Jokipii J. R. and P.J. Coleman 1968 *J. Geophys. Res.*, **73**, 17, 54955503
- [21] Bieber, J.W., W. H., Mathaeus, C. W., Smith, et al. 1994 *Astrophys. J.*, 420, 294-306