PROCEEDINGS OF SCIENCE

Turbulence-based model of the Forbush decrease of the galactic cosmic ray intensity

Anna Wawrzynczak
Institute of Computer Science, Siedlce University, Poland
E-mail: awawrzynczak@uph.edu.pl

Michael V. Alania*
Institute of Math. And Physics, Siedlce University, Poland
E-mail: alania@uph.edu.pl

We show that the source of the energy dependence of the rigidity spectrum of the Forbush decrease (Fd) of the galactic cosmic ray (GCR) intensity are the structural changes in the interplanetary magnetic field (IMF) turbulence driven by the shock waves either directly creating near the Sun or shock waves related to the propagation of the CME in interplanetary space. We recognize that during the Fd is observed the 3-D turbulence of the IMF unlike to the ideal slab/2-D model. This turbulence generally is stipulated by fluctuations of the Alfven waves in all three spatial directions. We assume that Bx and By components of the IMF are contributing in drift effect owing to theirs regular parts, while Bz does not, because of it consists only from the fluctuations. We incorporate in the 3D non-stationary model of the Fd the changes of the turbulence obtained from the IMF data during the Fd in October-November 2003. Based on the modeling of the GCR transport in the heliosphere we examine what conditions must be fulfilled to obtain the energy dependence of the rigidity spectrum of the Fd from the model. We present that the assumption of the rigidity dependence of exponent ν of the power spectral density of the IMF results in the rigidity dependence of the rigidity spectrum exponent γ. Exponent γ does not respond to the changes of the solar wind velocity, though amplitudes of the Fd of the GCR intensity depend on different levels of convection.

The 34th International Cosmic Ray Conference,
30 July- 6 August, 2015
The Hague, The Netherlands

*Speaker.

PoS(ICRC2015)216

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]. 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. The rigidity dependence of the GCR intensity in different phases of the Fd was presented in [4, 5, 6, 7, 8, 9, 10] 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. 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) [4, 5, 6, 7, 8, 9, 10]. Precisely, changes in the exponent γ of the power law rigidity R spectrum are explicitly determined by the changes of the exponent ν 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 ν is exponent of the PSD of the IMF turbulence e.g.[11, 12, 13].

The connection between the exponents γ and ν entails an expectation of the rigidity dependence of the exponent γ arising from the changes in the exponent ν versus frequency. The clearly recognized dependence of the exponent γ of the rigidity spectrum of the Fd on the rigidity of GCR particles during September 9-23, 2005 was presented in [9] and during November 5-20, 2004 in [14]. The rigidity spectrum of the GCR intensity variations during the Fd was hard for lower energy range and is soft for the higher energy range. Correspondingly, the consistent frequency dependence of the exponent ν of the PSD of the IMF components during the Fd was observed.

In this paper, we demonstrate the existence of the rigidity dependence of the exponent γ during the vast successive Fds in October-November 2003. Furthermore, we present 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 ν during the Fds is clearly manifested. Applying this observation to the model of the Fd we show that the decrease of the exponent ν with decreasing frequency lead to the soft rigidity spectrum of the Fd for GCR particles with higher rigidities.

2. Experimental data: Rigidity spectrum and the PSD of the IMF during Fd

Features of successive Fds of the GCR intensity in October - November 2003 have been studied previously considered based on the neutron monitors data in [4, 5]. We presented that the rigidity spectrum of the GCR intensity in the course of the first Fd (22 - 27 October) is gradually hardening, while the rigidity spectrum of the second Forbush effect (28 October - 10 November) from the beginning is very hard and softens progressively during the recovery phase of the GCR intensity. Now, we investigate whether we observe the rigidity dependence of the rigidity spectrum exponent

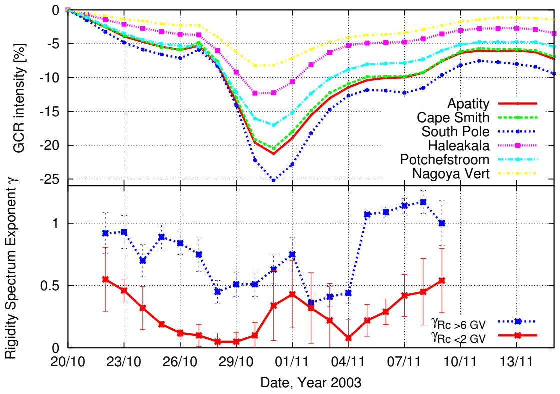

Figure 1: *Top panel*: Three day averaged temporal changes of the GCR intensity for the Apatity, Cape Smith, South Pole, Haleakala, Potchefstroom neutron monitors and Vertical channel of Nagoya muon telescope during the Fd. *Bottom panel*: Temporal changes in the rigidity spectrum exponent γ based on the data of the stations divided into two groups according to their cut-off rigidities.

γ for this Fds. For this purpose, we calculated the rigidity spectrum of the Fds based on the GCR intensity from 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 ($R_c < 2GV$) cut-off rigidities were stations: Apatity, Cape Smith, McMurdo, South Pole and Tixie Bay, whereas in the group of station with high cut-off ($R_c > 6GV$) rigidities were: Alma-Ata, Athens, Beijing, Haleakala, Mexico, Potchefstroom and following channels of Nagoya muon telescope: N0VV, N1EE, N1NN, N3EE.

The rigidity spectrum exponent γ of the power law rigidity spectrum $\delta D(R)/D(R) \propto AR^{-\gamma}$ was found based on the method in detail described in [9]. We calculated the rigidity spectrum exponent γ of Fd for each day of October 22- November 9, 2003. We considered smoothed over 3 days daily data to reveal reliable average temporal changes in the rigidity spectrum exponent γ and its energy dependence. Fig. 1 illustrates that time profile of γ is approximately the same for both cut-off rigidity groups. Nonetheless, the values of γ are larger for the group with higher cut-off rigidities. The value of $\gamma_{R_c>6GV}$ changes from $\gamma_{R_c>6GV} = 0.92 \pm 0.16$ at the beginning of the Fd down to $\gamma_{R_c>6GV} = 0.45 \pm 0.09$, and increases again in the recovery phase up to $\gamma_{R_c>6GV} = 1.17 \pm 0.09$. In turn, the exponent $\gamma_{R_c<2GV}$ estimated based on the low cut-off stations data is smaller by factor of 0.5, changing from $\gamma_{R_c<2GV} = 0.55 \pm 0.25$, through $\gamma_{R_c<2GV} = 0.05 \pm 0.07$ up to $\gamma_{R_c<2GV} = 0.54 \pm 0.25$. Accordingly, 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 [9, 14].

Hitherto in [4, 5] we presented that during the Fds in October - November 2003 we observe an increase of the exponent ν of the PSD of the IMF components. However, it was done based on 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 Fds. This fallouts from the requirement of using relatively long data series to attain the value of the exponent ν in low frequency range

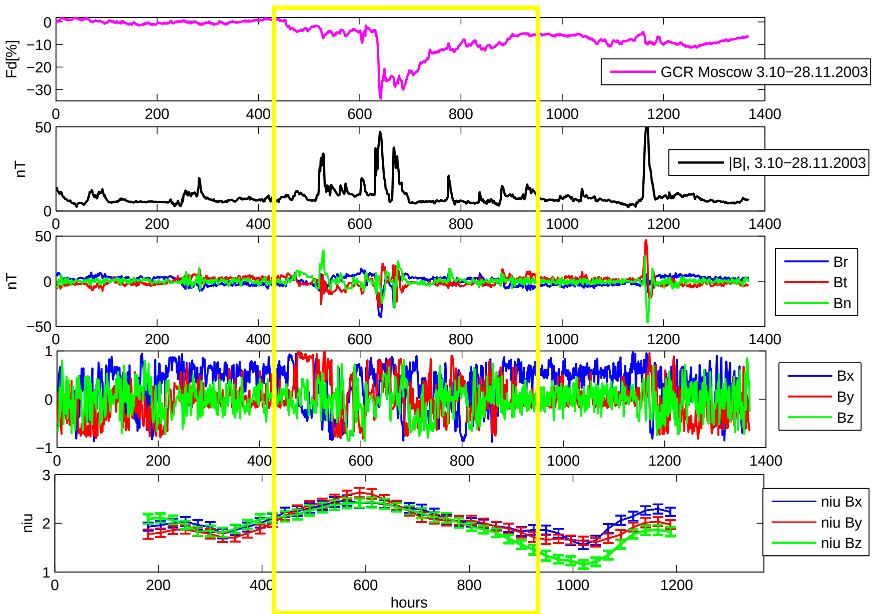

Figure 2: From the top panel: The hourly changes of: 1)the GCR intensity measured by the Moscow neutron monitor; 2) the IMF strength; 3) its components in the RTN [15] and 4) in the mean field coordinate system; 5) the values of the exponent ν of the PSD for IMF components based on the 15 days running series of hourly IMF data in October 3 - November 28, 2003.

($f \in [10^{-6}, 10^{-5}]$) 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 calculations, we use the hourly data of the IMF components recorded by the ACE spacecraft [15] for the period of October 3, 2003 - November 28, 2003 (Fig. 2). To reduce the problem of cross-talking between the IMF we converted the IMF from RTN to the mean field reference system [16]. 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 note the time changes of the exponent ν we estimated the PSD for 15-days long series of 1-hour data (360 hours) shifted by 24-hours. The top panel in the Fig. 2 provides the corresponding changes of the GCR intensity registered by the Moscow neutron monitor; the three following panels provide the IMF components used in calculations. The bottom panel in Fig. 2 presents the found values of the exponent ν of the PSD ($PSD \propto f^{-\nu}$). We assigned the value of ν in the center of the data series used in its calculation. One can see the gradual increase in the exponent ν for all IMF components when we approach the period of the Fds (marked in Fig. 2 by yellow box), and then its gradual decrease when Fds are over. Moreover, we can see that the time profile of ν for *Bx*, *By* and *Bz* components are very similar. We assume that during this Fds the 3-D turbulence of the IMF is stipulated by fluctuations of the Alfvenic waves in all three spatial directions.

The comparison of the time profiles of the rigidity spectrum exponent γ (Fig. 1) and the exponent ν Fig. 2 of the PSD of the IMF components during the series of Fds in October - November

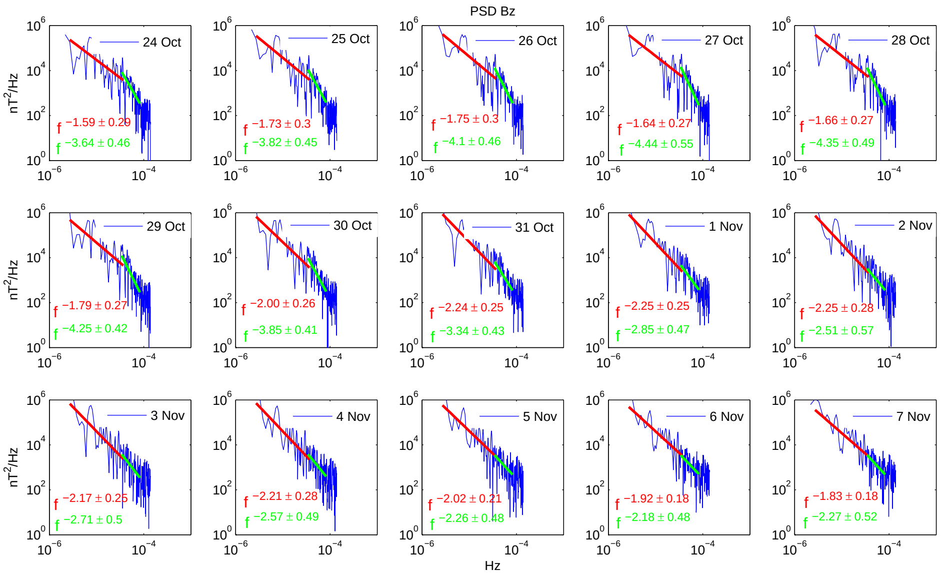

Figure 3: The PSD for the IMF component *Bz* based on the 15 days running series of hourly data in October - November 2003. The slope of the PSD estimated in two frequency intervals, the first - I-$[2.7\times10^{-6}Hz, 3.7\times10^{-5}Hz]$, and the second one II-$[3.4\times10^{-5}Hz, 8\times10^{-5}Hz]$.

2003 shows that we indeed observe the inverse relation between these exponents. However, based on the experimental data analysis difficult is to present the one to one correspondence. The reason is that the single value of exponent ν always describes the averaged state of the IMF turbulence for the data series employed in calculations. In this context, the calculation of the exponent γ can be seen as more precise because the rigidity spectrum of the GCR intensity can be calculated for the arbitrary time interval, restricted only by the neutron monitors and muon telescopes resolution.

The robust relation between the exponents γ and ν is also confirmed by changes of the exponent ν versus frequency presented in Fig. 3. Fig. 3 presents that in the main phase of the Fds we observe the significant increase of the slope in the higher frequency range. In the lower frequency range in which GCR particles with higher energies are modulated we have smaller exponent ν, than in the upper-frequency range in which are modulated lower energy particles. This is in coincidence with the energy dependence of the exponent γ of the rigidity spectrum (Fig. 1); i.e. the growth of the exponent γ for higher energy GCR particles.

3. The 3-D nonstationary model of the Forbush decrease

We model the Fd of the GCR intensity based on the Parker time-dependent transport equation [17]:

$$\frac{\partial f}{\partial t} = \vec{\nabla}\cdot(K_{ij}^{S}\cdot\vec{\nabla} f) - (\vec{v}_d + \vec{U})\cdot\vec{\nabla} f + \frac{R}{3}(\vec{\nabla}\cdot\vec{U})\frac{\partial f}{\partial R}, \tag{3.1}$$

where $f = f(\vec{r}, R, t)$ is an omnidirectional distribution function of three spatial coordinates $\vec{r} = r(r, \theta, \varphi)$, particles rigidity R and time t; $\vec{U}$ is solar wind velocity, $\vec{v}_d$ the drift velocity, and K_{ij}^{S}

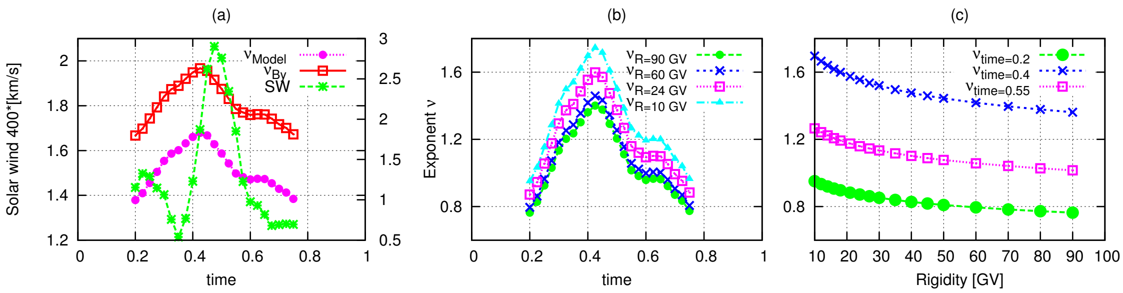

Figure 4: The included in the model of the Fd changes of the: (a) exponent ν for the By component and the solar wind velocity observed in the period of October, 18- November, 9, 2003; (b) time profiles of the exponent $\nu(t,R)$ for various rigidities; and (c) the changes of the exponent $\nu(t,R)$ versus rigidity.

is the symmetric part of the diffusion tensor of the GCR particles. We implement a drift velocity of GCR particles as, $\langle v_{d,i} \rangle = \frac{\partial K_{ij}^{(A)}}{\partial x_j}$ [18], where the anisotropic diffusion tensor $K_{ij} = K_{ij}^S + K_{ij}^A$ is given in [19]. The heliospheric magnetic field vector $\overrightarrow{B}$, supposing that IMF is two dimensional ($B_\theta = 0$), we assumed as $\overrightarrow{B} = (1 - 2H(\theta - \theta^{'})) \cdot (B_r \overrightarrow{e_r} + B_\varphi \overrightarrow{e_\varphi})$ [20]. The H is the Heaviside step function changing the sign of the global magnetic field in each hemisphere, $\overrightarrow{e_r}$ and $\overrightarrow{e_\varphi}$ are the unite vectors directed along the component $\overrightarrow{B_r}$ and $\overrightarrow{B_\varphi}$ of the IMF and $\theta^{'}$ corresponds to the heliolatitudinal position of the heliospheric neutral sheet (HNS). In the presented models $\theta^{'} = 57^\circ$ as given by Wilcox Solar Observatory for CR 2143. The HNS drift was taken into account according to the boundary condition method [20]. Implementation of the Parker heliospheric magnetic field is done through the spiral angle $\psi = arctan(-B_\varphi / B_r) = atan(\Omega r sin\theta / U)$ in anisotropic diffusion tensor of GCR particles.

We incorporated in the model of the Fd obtained from the experimental data changes of the exponent ν during the Fds in October-November 2003 presented in Fig. 3. Seeing that for all IMF components we observe the similar time profiles we decided to include in the model the changes of ν for the By component Fig. 4a. The changes of the IMF turbulence should be taken into account in the diffusion coefficient K_{II} of GCR, which depends on the rigidity R, as $K \propto R^{2-\nu}$ e.g.[11, 12, 13]. However, the estimated from data ν exceeds in the primary phase of the Fds the value of 2. Thus, before incorporating it into the model we have shifted it down by the factor of 0.8, i.e. $\nu_{model}(t) = \nu_{By} - 0.8$ (Fig. 4a). Additionally, to imitate the observed changes of ν versus the frequency (Fig. 3) we have added the dependence of the ν on particles rigidity (Fig. 4bc). Consequently, the changes of the IMF turbulence during the Fd are taken into account in the changes of the diffusion coefficient having a form: $K_{\|} = K_0 K(r) K(R,t)$, were $K_0 = 4.2 \times 10^{21}\ cm^1/s$, $K(r) = 1 + 0.5r$. The decrease of the diffusion coefficient takes place due to the increase of the IMF turbulence, as $K(R,t) = R^\alpha = R^{2-\nu(t,R)}$. The exponent ν in the vicinity of space responsible for the Fd is expressed as: $\nu(t,R) = \nu(t) \cdot \nu(R)$ where $\nu(t) = \nu_{By} - 0.8$ and $\nu(R) = 1.2 \cdot R^{-0.1}$(Fig. 4). Furthermore, the dependence of the parallel diffusion coefficient K_{II} on ν 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 ω is particle angular velocity and τ 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

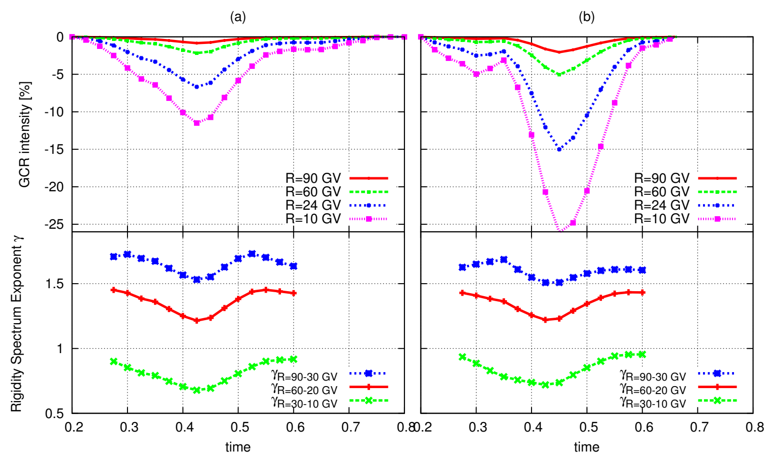

Figure 5: Changes of the expected amplitudes of the Fd of the GCR intensity for various rigidities at the Earth orbit and the corresponding changes of the expected rigidity spectrum exponent γ in three rigidity ranges based on the solution of the two models of the Fd with (a) constant solar wind velocity and (b) included changes of the solar wind velocity.

$3 \leq \omega\tau \leq 5$.

Taking into account assumptions above the Eq. (3.1) was solved numerically with the numerical method in details presented in [21]. The obtained amplitudes of the Fd for the rigidity $R = 90, 60, 24, 10GV$ presents the top panel in Fig. 5a. The calculated temporal changes of the power law rigidity spectrum exponents γ ($\frac{\delta D(R)}{D(R)} = \frac{1}{f}\frac{df}{dR} \propto R^{-\gamma}$) in three rigidity intervals presents the bottom panel in Fig. 5a. We can see that incorporating into the model of the Fd only changes of the exponent $\nu(t,R)$ of the PSD of the IMF turbulence we obtain comparable with observational rigidity dependence of the power low rigidity spectrum exponent γ , but amplitude of the Fd is much less than the observed one. Thus, we additionally included in the model the five-day smoothed changes of the solar wind velocity registered by ACE in the period of October, 18-November, 9, 2003 presented in Fig. 4a. The corresponding modeling results shows Fig. 5b. In this case, we obtain the greater amplitude of the Fd being in agreement with the observed one (Fig. 2). However, the inclusion of the increase of the solar wind velocity didn't influence much the rigidity spectrum exponent γ. We can state that model of the Fd is more realistic when the changes of both-the solar wind velocity U and the exponent $\nu(t,R)$ are implemented in transport equation (3.1).

4. Conclusion

We presented the dependence of the exponent γ of the rigidity spectrum of the Fds in October - November 2003 versus the GCR particles energy. The rigidity spectrum exponent γ is the larger, the higher are cut-off rigidities of stations used in calculations. We estimated the daily time evolution of the exponent ν of the PSD of the IMF components throughout the Fd. Results show the gradual increase of the exponent ν up to the primary phase of the Fd and then its gradual return to the initial level. The presented dependence of the exponent ν of the PSD of the IMF turbulence upon frequency during the Fd support the relationship between the rigidity spectrum exponent γ

and the exponent ν.

We proposed models of the Fd incorporating obtained from the experimental data changes of the IMF turbulence during the Fds in October-November 2003. Modeling calculations are compatible with the results obtained based on the neutron monitors, ground muon telescopes and IMF data and confirms the general dependence of the expected rigidity spectrum exponent γ of the Fd on the exponent ν of the PSD of the IMF turbulence. Moreover, the assumption of the rigidity dependence of ν results in the rigidity dependence of γ. Exponent γ does not respond to the changes of the solar wind velocity (changes of convection), though amplitudes of the Fd of the GCR intensity depend on different levels of convection.

Acknowledgments

We are grateful to the Principal Investigators of the worldwide network of neutron monitors, Nagoya muon telescope and Advanced Composition Explorer spacecraft for access to the data.

References

[1] Forbush S.E. 1937 *Phys. Rev.*, **51** , 1108-1109

[2] Burlaga L.F. 1995 *Interplanetary Magnetohydrodynamics*, (New York: Oxford Univ. Press)

[3] Cane H.V. 2000 *Space Sci. Rev.*, **93**, 55âĂŞ77

[4] Wawrzynczak A., Alania M.V. 2005 *Adv.in Space Res.* , **35**, 682-686

[5] Wawrzynczak A., Alania M.V., 2005 *Acta Phys. Polonica B*, **36** , 5, 1847-1854,

[6] Wawrzynczak A., Alania, M.V.2008 *Adv. in Space Res.* **41** 2, 325-334

[7] Alania M.V.,Wawrzynczak A. 2008*Astrophys. And Space Sci. Transactions*, **4** , 59-63

[8] Wawrzynczak A., Alania M.V. 2010 Adv. *Adv. Space Res.*, **45**, 5, 622-631

[9] Alania M.V. , A. Wawrzynczak 2012 *Adv. in Space Res.*, **50**, 725-730

[10] Alania M.V., A. Wawrzynczak, V. E. Sdobnov and M. V. Kravtsova 2013 *Solar Phys.*, **286**, 561-576

[11] Jokipii J.R. 1966 *Astrophys. J.*, **146**, 480-487

[12] Toptygin I.N. 1985 *Cosmic rays in interplanetary magnetic fields*, (Reidel Publishing Company)

[13] Shalchi A. 2009 *Nonlinear Cosmic Ray Diffusion Theories*, (Springer)

[14] Wawrzynczak A., Alania, 2015 , *Proc. of the 24th European Cosmic Ray Symposium* (in print)

[15] *http://www.srl.caltech.edu/ACE/ASC/level2/index.html*

[16] Bruno R and V. Carbone 2013 *Living Rev. Solar Phys*, **10**

[17] Parker E.N. 1965 *Planet. Space Sci.*, **13**, 9-49

[18] Jokipii J.R., Levy E.H., Hubbard W.B., 1977 *Astrophys. J.* , **213**, 861-868

[19] Alania M.V., 2002 *Acta Physica Polonica B*, **33** , 4, 1149-1165,

[20] Jokipii J.R., Kopriva D.A. 1979 *Astrophys. J.*, **234** , 384-392

[21] Wawrzynczak A., Alania M.V., 2010 *Lecture Notes in Computer Science*, **6067** , Part I, 105-114