FLUCTUATIONS OF THE INTERPLANETARY MAGNETIC FIELD DURING THE FORBUSH EFFECTS OF GALACTIC COSMIC RAYS*

A. Wawrzynczak

Institute of Computer Science, University of Podlasie
Sienkiewicza 51, 08-110, Siedlce, Poland

and M.V. Alania

Institute of Mathematics and Physics, University of Podlasie
3 Maja 54, 08-110 Siedlce, Poland
Institute of Geophysics, Georgian Academy of Sciences, Tbilisi, Georgia

(Received January 12, 2005)

Dedicated to Professor Andrzej Fuliński on the occasion of his 70th birthday

The rigidity spectra for two consecutive Forbush effects (October–November 2003) of the galactic cosmic ray intensity estimated by use of the experimental data from neutron monitors are significantly different. The rigidity spectrum gradually hardens in the course of the first Forbush effect (October 22–28). On the contrary, it is very hard at the beginning of the second Forbush effect (October 29 to November 10). The rigidity spectrum progressively softens during the recovery phase of the galactic cosmic ray intensity. It is assumed that the peculiarities of the rigidity spectrum of the Forbush effects are related to the enhancement of the power within the energy range of the interplanetary magnetic field turbulence during the major phase of the Forbush effects. The additional large scale irregularities of the interplanetary magnetic field should be created due to the interaction of the extending high speed disturbances with the background solar wind. This assumption is confirmed by the analysis of the interplanetary magnetic field data. During the major phase of the Forbush effects the power spectral densities of the components of the interplanetary magnetic field are significantly larger than before and after the Forbush effects.

PACS numbers: 96.40.Cd, 96.50.Ci, 96.50.Fm

* Presented at the XVII Marian Smoluchowski Symposium on Statistical Physics, Zakopane, Poland, September 4–9, 2004.

1. Introduction

According to the quasi linear theory [1,2] the diffusion coefficient χ of the galactic cosmic ray (GCR) transport [3,4] depends on the rigidity R of the GCR particles as, $\chi \propto R^{\alpha}$ and $\alpha = 2 - \nu$; ν is the exponent of the power spectral density (PSD) of the interplanetary magnetic field (IMF) fluctuations (PSD$\propto f^{-\nu}$ where f is the frequency). In [5,6] it was found that the exponent γ of the rigidity spectrum $\delta D(R)/D(R) = AR^{-\gamma}$ (where R is the rigidity of the GCR particles and A is the amplitude of the GCR variations in the heliosphere) of the long period variations of the GCR intensity is related to the structure of the IMF fluctuations, $\gamma \propto \alpha$ ($\gamma \propto 2 - \nu$). Moreover, in Ref. [6-8] it was documented that the diffusion–convection approximation of the GCR transport and the relation $\gamma \propto 2 - \nu$ are valid for the Forbush effects of the GCR intensity. The temporal changes of the exponent ν of the PSD of the IMF's fluctuations can be estimated using the temporal changes of the rigidity spectrum exponent γ of the Forbush effect based on the relation $\gamma \propto 2 - \nu$. The exponent ν can be determined for the arbitrary period in the course of the Forbush effects; the duration of the period should be defined only by the accuracy of the GCR intensity data using for the calculations of the rigidity spectrum exponent γ of the Forbush effect [6–8]. Generally, Forbush effects last averagely 5–10 days and are caused by the powerful disturbances in the interplanetary space associated with the coronal mass ejecta and solar flares [9–11]. However, data of the IMF for the period of the main phase of the Forbush effect are not sufficient to estimate the exponent ν of the PSD in the energy range of the IMF's turbulence ($f < 10^{-5}$ Hz). Therefore, data of the GCR intensity variations during the Forbush effects are of great value for estimation of the temporal changes in the structure of the IMF turbulence. The purpose of this paper is to study the feature of the temporal changes of the rigidity spectrum exponent γ of two consecutive Forbush effects of the GCR intensity in October–November 2003 and its relation to temporal changes of the IMF turbulence.

2. Experimental data and methods

The rigidity spectrum of two consecutive Forbush effects of the GCR intensity in October–November 2003 and the changes of the structure of the IMF's turbulence are studied using the data from neutron monitors [13]. The average intensity N_0 for each neutron monitor during the October 19–21 was accepted as a reference level (100%). The amplitudes $\delta J_i/J_i$ of the intensity variation were calculated as follows:

$$\frac{\delta J_i}{J_i} = \frac{N - N_0}{N_0}\,,$$

where N is daily average count rate of neutron monitor. The rigidity spectrum of the Forbush effect can be expressed [11, 12] as

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

where $R_{\max}$ is the upper limiting rigidity beyond which the Forbush effect of GCR intensity vanishes; A is the amplitude of the Forbush effect in the heliosphere. At any point of observation (by a neutron monitor) the amplitude $\delta J_i/J_i$ of the GCR intensity variation with the geomagnetic cut-off rigidity R_i and the average atmospheric depth h_i is defined as [11]:

$$\frac{\delta J_i}{J_i} = \int\limits_{R_i}^{R_{\max}} \frac{\delta D(R) W_i(R, h_i) dR}{D(R)}\,, \tag{2}$$

where $W_i(R, h_i)$ is the coupling coefficient. Smoothed (over 3 days) time profiles of the GCR intensity variations $\delta J_i/J_i$ based on Athens (A), Climax (C) and Kiel (K) neutron monitors data for the period of October 21 to November 10, 2003 are presented in Fig. 1(a). The first Forbush effect took place during October 22–27, while the second Forbush effect was observed throughout October 28 to November 10, 2003. For the power rigidity spectrum (1) the expression (2) can be rewritten

$$\frac{\delta J_i}{J_i} = A_i \int\limits_{R_i}^{R_{\max}} R^{-\gamma} W_i(R, h_i) dR\,. \tag{3}$$

From (3) one can obtain

$$\frac{\delta J_i/J_i}{A_i} = \int\limits_{R_i}^{R_{\max}} R^{-\gamma} W_i(R, h_i) dR\,. \tag{4}$$

The amplitude A_i of the Forbush effect in the heliosphere must be the same for the arbitrary neutron monitor within the limit of the accuracy of calculations. Therefore, the temporal changes of the energy spectrum exponent γ can be found by the minimization of the expression

$$\phi = \sum_{i}^{n} (A_i - \overline{A}) \tag{5}$$

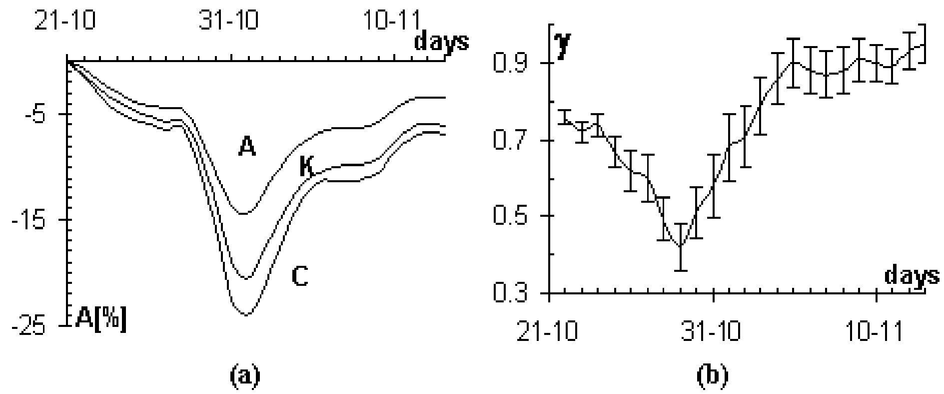

Fig. 1. (a) Temporal changes of the GCR intensities for the period of October 21 to 13 November, 2003, A — Athens, K — Kiel, C — Climax; (b) rigidity spectrum of this Forbush effects for the same period.

with respect to $R_{\max}$ and γ (where $\bar{A} = \frac{1}{n}\sum_i^n A_i$, n is the number of neutron monitors with different cut-off rigidities). The values of the integral $\int_{R_i}^{R_{\max}} R^{-\gamma} W_i(R, h_i) dR$ for different magnitudes of the $R_{\max}$ and γ are given in [12]. The minimal values of ϕ by means of the daily amplitudes of the Forbush effects in October–November 2003 were obtained generally for the $R_{\max} \geq 90$–100 GV and for the very particular values of γ based on the data of eight ($n = 8$) neutron monitors with different cut-off rigidities (Apatity — 0.65 GV, Athens — 8.72 GV, Climax — 3.03 GV, Halekala — 13.3 GV, Irkutsk — 3.66 GV, Kiel — 2.29 GV, Moscow — 2.46 GV, Oulu — 0.81 GV). Results of calculations of the rigidity spectrum exponent γ of the consecutive Forbush effects taking place between October 21 and November 10 is presented in Fig. 1(b).

3. Discussion

As it can be inferred from Fig. 1(b), the rigidity spectrum of the first Forbush effect is relatively soft ($\gamma \approx 0.8$) at the beginning phase (October 22) and it gradually hardens in time taking on value ($\gamma \approx 0.5$) on October 28. In contrast, the rigidity spectrum of the second Forbush effect is very hard ($\gamma \approx 0.45$) at the beginning phase (October 29–30) and then it progressively softens during the recovery period of the GCR intensity. In order to explain the observed features of the rigidity spectrum it was postulated that the additional large scale irregularities of the IMF (Alfven or magnetosonic waves of large length) are generated in the interplanetary space. The generation of the new large scale irregularities of the IMF must be related to the nonlinear interaction of the high speed disturbances with the background solar wind. The process of creation of the additional large scale irregularities must have been completed generally during the period of October 22–29, according to the temporal changes of the rigidity spectrum exponent γ (*cf.* Fig. 1(b)). The other argument for the confirmation of this postulate is the observation of the daily variations in the rigidity spectra calculated separately for the first (October 21–28) and for the second Forbush effect (October 29 to November 10). The amplitudes of the second Forbush effect were calculated with respect to the average intensity for October 26–28, taken as a reference level (100%). The changes of the smoothed (over 3 days) GCR intensity of the first and the second Forbush effects are presented in Figs. 2(a) and 2(b), and the corresponding rigidity spectra in Figs. 2(c) and 2(d).

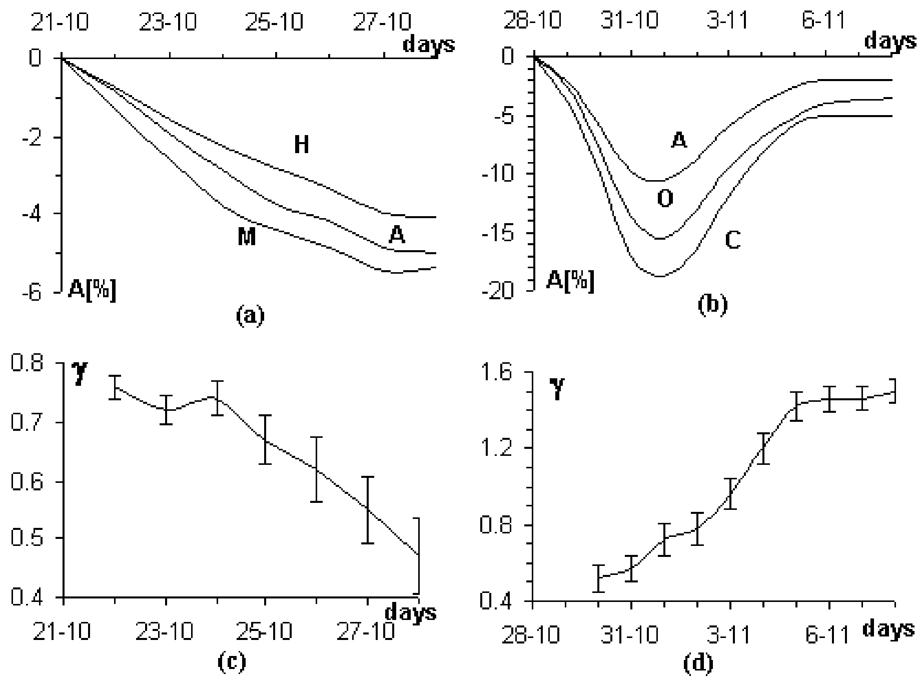

Fig. 2. Temporal changes of the GCR intensities for period of: (a) October 21–27, H — Halekala, A — Athens, M — Moscow, (c) October 28 to November 10, A — Athens, O — Oulu, C — Climax. Rigidity spectrum of the Forbush effect for the periods: (b) October 21–27, (d) October 28 to November 10.

As it can be deduced from Fig. 2(d) rigidity spectrum of the second Forbush effect is very hard since the beginning phase ($\gamma \approx 0.4$) and basically coincides with the final point value of the exponent γ for the first Forbush effect ($\gamma \approx 0.45$). Following our assumption this feature of the rigidity spectrum could be related to the appearance of the new large scale irregularities of the IMF. These irregularities are produced during the first and at the initial stage of the second Forbush effects. The assumption of possible existence of additional relatively large scale Alfven (or magnetosonic) waves in the IMF's turbulence can be verified by the analysis of power spectra (PS) of fluctuations in the IMF's components B_x, B_y, B_z before (period I), during (period II) and after the Forbush effects (period III). The duration of the Forbush effects October 22 to November 9 (period II) is predetermined, so in order to have the comparable statistics for the periods I and III, data of the October 3–21 is considered as the period I and data of the November 10–28 as the period III. The distributions of the PS of the fluctuations for all components of the IMF are presented in Figs. 3(a), (b), (c).

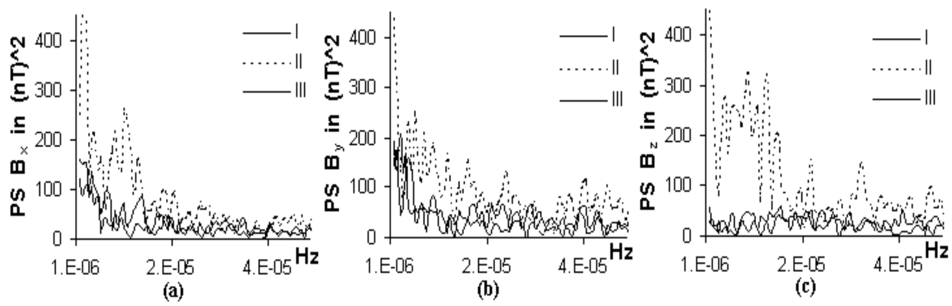

Fig. 3. PS of the (a) B_x , (b) B_y and (c) B_z component of the IMF fluctuations observed by ACE for periods: before the Forbush effect (I), during (II) and after (III) the Forbush effect in the frequency range $2 \times 10^{-6}\,\mathrm{Hz} \leq f \leq 1 \times 10^{-4}\,\mathrm{Hz}$.

It can be seen (Figs. 3(a), (b) (c)) that the significant enhancements of the fluctuations in the IMF's components are observed (dashed curves) during the main phase of the Forbush effects (period II). Unfortunately, the series of the IMF's experimental data are limited by the duration of the Forbush effect. Nevertheless, the power spectra PS of the IMF's components during the Forbush effects give an opportunity to judge about concerning temporal changes of the energy range of the IMF turbulence. The region of the IMF's turbulence ($< 10^{-5}$ Hz) is responsible for the scattering of GCR particles to which neutron monitors are sensitive (5–50 GV).

In order to study in more detail the temporal changes of the exponents ν of the PSD for IMF's components fluctuations in the periods before, during and after the Forbush effects the six separate time intervals: 7–13, 14–21 and October 22–28, 29 October–4 November, 5–11 November and 12–18 November were considered. The temporal changes of the exponents ν of the PSD of the all IMF's components for six time intervals are presented in Fig. 4 and in Table I.

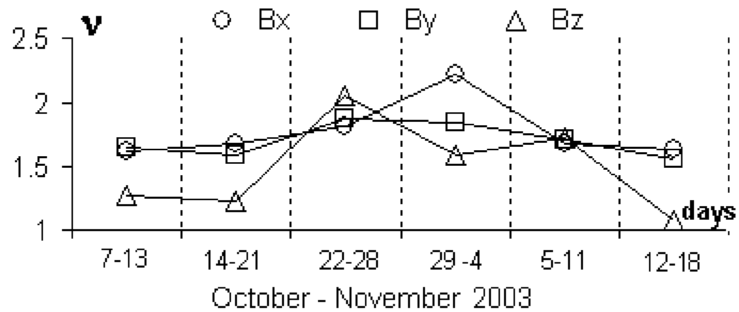

Fig. 4. Temporal changes of the exponent ν of the PSD of the B_x, B_y and B_z components of the IMF.

TABLE I

The eksponent ν of the PSD of the IMF's components for six time intervals.

Components of the IMF	ν Oct. 7–13	Oct. 14–21	Oct. 22–28	Oct. 29 Nov. 4	Nov. 5–11	Nov. 12–18
B_x	1.62	1.69	1.81	2.22	1.68	1.64
B_y	1.66	1.59	1.87	1.84	1.71	1.56
B_z	1.26	1.23	2.05	1.59	1.73	1.08

It can be observed that the exponent ν of the PSD of the IMF's components increases significantly during the main phase of the Forbush effects. Thus, the hypothesis of the generation of the additional large scale irregularities of the IMF's turbulence during the Forbush effects of the GCR intensity as assumed, based on the investigations of the temporal changes of the rigidity spectrum exponent γ, is confirmed by the analysis of the data of the IMF.

4. Conclusion

1. The rigidity spectrum of the GCR intensity variations is relatively soft for the beginning phase (October 22) of the first Forbush effect and then it is gradually hardening up to October 28. The rigidity spectrum of the second Forbush effect is very hard at the beginning phase (October 29–30) and softens progressively during the recovery phase of the GCR intensity.

2. The significant enhancement of the fluctuations of the B_x, B_y and B_z components of the IMF is observed during the main phase of the Forbush effects; it is caused by the appearance of the additional large scale irregularities of the IMF (Alfven or magnetosonic waves of relatively large length) generated due to the nonlinear interaction of the extending high speed disturbances with the background solar wind. The specific feature of the rigidity spectrum of the consecutive Forbush effects of GCR intensity in October–November 2003 could be ascribed to the changes of the structure of the IMF turbulence.

The authors thank the researchers of the Advanced Composition Explorer Spacecraft and Apatity, Athens, Climax, Halekala, Irkutsk, Kiel, Moscow, Oulu neutron monitor stations. We also thank the referee for the valuable remarks and suggestions.

REFERENCES

[1] J.R. Jokipii, *Reviews of Geophysics and Space Physics* **9**, 21 (1971).

[2] I.N. Toptygin, "Cosmic Rays in Interplanetary Magnetic Fields", Reidel Publishing Company, 1985.

[3] E.N. Parker, *Astrophys. J.* **128**, 664 (1958).

[4] E.N. Parker, *Planet. Space. Sci.* **13**, 9 (1965).

[5] M.V. Alania, K. Iskra, *Adv. Space Res.* **16**, 241 (1995).

[6] M.V. Alania, A. Barczak, A. Wawrzynczak, *Acta Phys. Pol. B* **34**, 3813 (2003).

[7] M.V. Alania, J. Szabelski, A. Wawrzynczak, Proceedings of the 28-th ICRC, Universal Academy Press INC., Tokyo, Japan, 6, p. 3585, 2003.

[8] M.V. Alania, A. Wawrzynczak, *Acta Phys. Pol. B* **35**, 1551 (2004).

[9] S.E. Forbush, *J. Geophys. Res.* **59**, 525 (1954).

[10] H.V. Cane, *Space Sci. Rev.* **93**, 49 (2000).

[11] L.I. Dorman, *"Cosmic Rays Variations and Space Exploration"*, Nauka, Moscow 1963.

[12] S. Yasue, *et al.*, *"Coupling Coefficients of Cosmic Rays Daily Variations for Neutron Monitors"*, 7, Nagoya 1982.

[13] `http://www.srl.caltech.edu/ACE`