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On the Relationship of the Interplanetary Magnetic Field Turbulence and the Energy Spectrum of the Forbush Effects

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We study the peculiarities of the rigidity spectrum of the two consecutive Forbush effects in October-November 2003 and its relation with the interplanetary magnetic field (IMF) turbulence. The rigidity spectrum of the galactic cosmic ray (GCR) intensity gradually becomes hard during the first Forbush effect (22-27 October), while it is very hard since the beginning phase of the second Forbush effect (28 October-10 November) and then progressively becomes soft for the recovery phase of the GCR intensity. It is proposed that the hardening of the rigidity spectrum of the Forbush effects is related with the considerable enhancement of the power in the energy range of the IMF fluctuations during the major phase of the Forbush effects; mainly, the additional large scale irregularities of the IMF (Alfven/ or magnetosonic waves of the long length) should be created due to the interaction of the extending high speed disturbances with the background solar wind. It is shown that the power spectral densities of the all components of the IMF fluctuations are significantly larger during the major phase of the Forbush effects than before and after it.

1. Introduction

We assume that the diffusion coefficient χ of GCR transport depends on the rigidity R of the GCR particles as $\chi \propto R^{\alpha}$, according to the quasi linear theory [1-2]. The parameter $\alpha = 2-\nu$; and ν is the exponent of the power spectral density (PSD) of the IMF fluctuations ($PSD \propto f^{-\nu}$,and f is the frequency). In [3,4] 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, $\gamma \propto 2-\nu$. In [5-7] was shown that the diffusion-convection approximation of GCR transport is valid and the statement of $\gamma \propto 2-\nu$ can be extended for the great majority of sporadic Forbush effects (especially for the recovery period) and mainly for all the recurrent Forbush effects of the GCR intensity. So, the parameters γ and ν are strongly related. We assume that the hardening of the rigidity spectrum of the Forbush effects is related with the considerable enhancement of the power in the energy range of the IMF fluctuations during the major phase of the Forbush effects; mainly, the additional large scale irregularities of the IMF (Alfven/ or magnetosonic waves of the long length) should be created due to the interaction of the extending high speed disturbances with the background solar wind. 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 with the temporal changes of the IMF turbulence.

2. Experimental data and discussion

We study 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 using the data of neutron monitors and IMF [8]. The average intensity N_0 for each neutron monitor during the 19-21 October was accepted as a reference level (100%). The amplitudes $\delta Ji/Ji$ of the intensity variation were calculated, as follows: $\delta Ji/Ji = \frac{N-N_0}{N_0}$, where N is daily average count rate of neutron monitor. The rigidity spectrum of the Forbush effect can be expressed [9,10]:

$$\frac{\delta D(R)}{D(R)} = \begin{cases} AR^{-\gamma} \; for \quad R \le R_{\max} \\ 0 \quad for \quad R > R_{\max} \end{cases} \tag{1}$$

Where $\boldsymbol{R_{max}}$ 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. Smoothed (3 days) time profiles of the GCR intensity variations $\delta Ji/Ji$ based on Halekala (H), Climax (C) and Oulu (O) neutron monitors data for the period of 21 October – 10 November 2003 are presented in Figure1a. The first Forbush effect lasts during 22-28 October; while the second Forbush effect lasts throughout 29 October-10 November 2003. Results of calculations of the rigidity spectrum exponent γ of the consecutive Forbush effects 22 October – 10 November 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 and Oulu - 0.81 GV) is presented in Figure 1b.

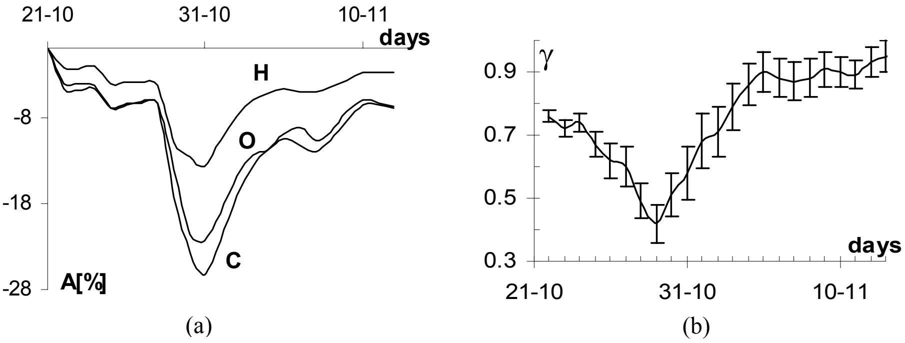

Figure 1. Temporal changes of the: (a) GCR intensity for period of 22 October – 13 November 2003 (H-Halekala, O-Oulu, C-Climax); (b) rigidity spectrum exponent γ of the Forbush effects for the same period

The rigidity spectrum (Figure 1b) of the first Forbush effect is relatively soft (γ ≈ 0.8) at the beginning phase (22 October) and then is gradually hardening up to 28 October (γ ≈ 0.5); the rigidity spectrum of the second Forbush effect is very hard (γ ≈ 0.45) at the beginning phase (29-30 October) and then is progressively softening during the recovery period of the GCR intensity. To explain the observed features of the rigidity spectrum there was postulated that in the extending disturbed vicinity of the interplanetary space (where Forbush effect is produced) the additional large scale irregularities of the IMF (Alfven /or magnetosonic waves of large length) should be generated. 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. A process of the creation of the additional large scale irregularities must be generally completed during the period of 22- 29 October according to the temporal changes of the rigidity spectrum exponent γ (Figure 1b). The further argument for the confirmation of this postulate are the daily changes of the rigidity spectra calculated separately for 22-28 October (the first Forbush effect) and for 29 October -10 November (the second Forbush effect). The amplitudes of the second Forbush effect were calculated with respect to the average intensity for October 26-28, considered it as a reference level (100%). The changes of the smoothed

(3 days) GCR intensity of the first and the second Forbush effects are presented in Figure 2a and 2c, and the corresponding rigidity spectra - in Figure 2b and 2d, respectively. As it is seen from the Figure2d the rigidity spectrum of the second Forbush effect is very hard since the beginning phase ($\gamma \approx 0.4$) and basically coincides with the last point value of the exponent γ for first Forbush effect ($\gamma \approx 0.45$). According to our assumption the gradually hardening of the rigidity spectrum of the first Forbush effect and the very hard rigidity spectrum since the beginning phase of the second Forbush effect could be connected with 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. An assumption of the possible existence of the new additional relatively large scale Alfven /or magnetosonic waves in the IMF's turbulence can be verified by the analyses of the distributions of the power spectrum (PS) of the fluctuations of the IMF's components B_x, B_y, B_z before the Forbush effects (I period), during (II period) and after the Forbush effects (III period). The duration of the Forbush effects 22 October–9 November (II period) is predetermined, so in order to have the comparable statistics for the I and III periods, data of the 3-21 October is considered as the I period and data of the 10-28 November as the III period. The distributions of the PS of the fluctuations for all components of the IMF are presented in figure 3.

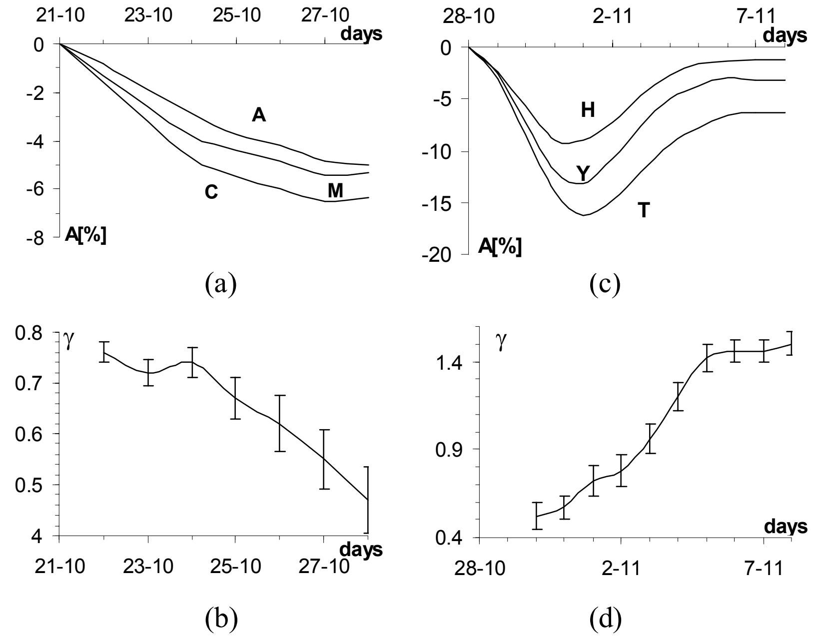

Figure 2abcd. Temporal changes of the GCR intensities for the periods : (a) 22-28 October 2003 A-Athens, M-Moscow, C-Climax, (c) 29 October -10 November 2003; H-Halekala, Y-Yakutsk, T-Thule; Changes of the rigidity spectrum of the Forbush effect for the periods: (b) 22-28 October 2003; (d) 29 October-10 November 2003

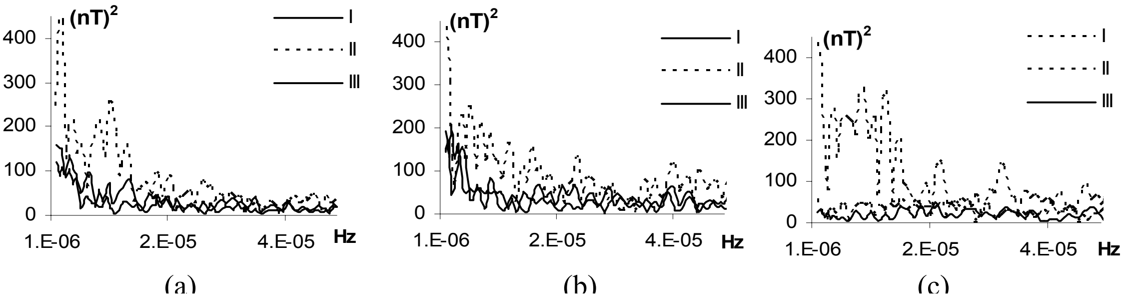

Figure 3. PS of the (a) B_x , (b) B_y and (c) B_z component of the IMF fluctuations observed by ACE for periods: before the Forbush effect (I), during (II) and after (III) the Forbush effect in the frequency range $2\times10^{-6}\,Hz \le f \le 1\times10^{-4}\,Hz$

The significant enhancements (Figure 3abc) of the fluctuations of the IMF's components are observed (red curves) during the main phase of the Forbush effects (II period). Unfortunately, the series of the IMF's experimental data are limited by the duration of the Forbush effect. Nevertheless, the PS of the IMF's components during the Forbush effects give an opportunity to judge concerning the temporal changes of the energy range of the IMF turbulence. This 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). 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 assumed based on the investigation of the temporal changes of the rigidity spectrum exponent γ is confirmed by the analyses of the data of the IMF. In addition, the temporal changes of the exponent ν of the PSD in the energy range of the IMF's turbulence ($f < 10^{-5}$ Hz) can be estimated using the temporal changes of the rigidity spectrum exponent γ of the Forbush effect based on the relation $\gamma \propto 2-\nu$; data of the IMF for the main phase period of the Forbush effect is not statistically sufficient for these calculations. Therefore, data of the GCR intensity variations during the Forbush effects becomes a very much valuable for the estimation of the temporal changes of the structure of the IMF turbulence.

3. Conclusion

1. The rigidity spectrum of the GCR intensity variations is relatively soft for the beginning phase (22 October) of the first Forbush effect and then it is gradually hardening up to 28 October, while rigidity spectrum of the second Forbush effect is very hard at the beginning phase (29-30 October) and then it progressively becomes soft 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 the relatively long length) generated due to the nonlinear interaction of the extending high speed disturbances with the background solar wind.

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