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Forbush decrease of the galactic cosmic ray intensity: experimental study and theoretical modeling

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Abstract. We study the temporal changes of the power law rigidity spectrum of the Forbush decrease (Fd) of the galactic cosmic ray (GCR) intensity. We show that the power law rigidity spectrum of Fd for the period of 6–20 November 2004 found by neutron monitors and ground muon telescopes experimental data, gradually is hardening during the decreasing phase of the intensities and then steadily is softening during the recovery phase. A relation of the rigidity spectrum exponent of the Fd of the GCR intensity with the exponent of the power spectral density (PSD) of the components of the interplanetary magnetic field (IMF) turbulence is established. We develop three dimensional (3-D) non stationary model of the Fd and show that the results of the theoretical modeling are in good agreement with the experimental data. We suppose that temporal changes of the rigidity spectrum exponent of the Fd of GCR intensity can be used to calculate the exponent of the PSD of the IMF turbulence for the arbitrary period, which is not achievable by the in situ measurements of the IMF.

1 Introduction

A fast decreases of GCR intensity during one-two days and then its gradually recovery in 5–7 days are called the Forbush decreases (Fds) (Forbush, 1937). They are formed after the outstanding flares on the Sun and intensive solar coronal mass ejecta (CME) (Burlaga, 1995; Cane, 2000). These phenomena appear randomly in time, sporadically without any regularity, increasing its frequency in maxima of the solar activity. Fd are of three basic types, (1) caused by a shock and ejecta, (2) caused by a shock only, and (3) caused by an ejecta only (Cane, 2000). Amplitude of the Fd of the GCR intensity is found as the difference between the intensities at the onset and the minimum point of Fd. A dependence of the amplitude on the rigidity of GCR particles is one of the fundamental characteristics of the Fd. Lots of papers are devoted to this problem. Cane (2000) notes that if rigidity dependence of the amplitude of Fds is given by power law $R^{-\gamma}$, γ ranges from about $0.4 \div 1.2$. The recently published paper Ahluwalia and Fikani (2007) is many-sided from the methodological, explanation, discussion, and even historical points of view. A selection of the response functions proposed by various authors (e.g. see in book Dorman, 2004), and calculation of the median rigidities of detectors to use them for the finding of the rigidity dependence of Fd (Ahluwalia and Fikani, 2007) need further study.

2 Motivation

We consider that an investigation of the rigidity dependence of Fd only by means of the amplitudes for the one point of the GCR intensity minimum is not sufficient. To study dynamics of the Fd there is necessary to consider a temporal changes of this dependence for different phases of the Fd. We are sure that it will shed light on physical processes taking place during the Fd. This consideration seems to be useful for the space weather problem, as well (Kudela et al., 2000). Studying several Fds we show that (Wawrzynczak and Alania, 2005, 2008) the changes of the rigidity R spectrum $\delta D(R)/D(R) \propto R^{-\gamma}$ of the Fds, determined using neutron monitors and ground muon telescopes data, is related with the changes of the PSD of the IMF's turbulence ($PSD \propto f^{-\nu}$, f is a frequency); namely the exponent γ depends on the exponent ν in the range of frequency of the IMF turbulence, $f \sim 10^{-6} \div 10^{-5}$ Hz, to which neutron monitors and ground muon telescopes respond. We suppose that a relationship between the exponent γ of the rigidity spectrum of the Fd of the GCR intensity and the expo-

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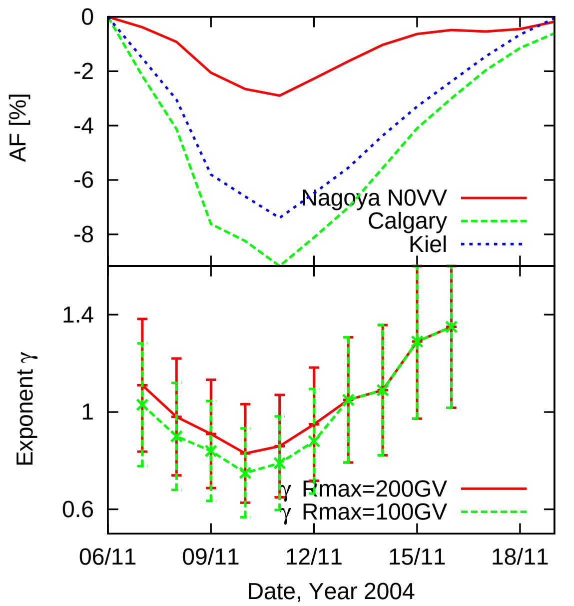

Fig. 1. Temporal changes of the GCR intensities (top panel) and temporal changes of the rigidity spectrum exponent γ (bottom panel) during the Fd of 6–20 November 2004

nent ν of the PSD of the IMF turbulence (Wawrzynczak and Alania, 2005, 2008) 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 should be 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 $\alpha = 2 - \nu$ (Jokipii, 1966; Hasselman and Wibberenz, 1968; Jokipii, 1971; Toptygin, 1985). So, it is obvious that a correlation of the power spectrum of the IMF with diffusion coefficient (with the mean free path of the GCR particles along the IMF) is expected from QLT. It should be noted that a conclusion of Jokipii (Fig. 4 in Jokipii, 1971) about transition rigidity 2 GeV, above which diffusion coefficient K is proportional to R^2 ($K \propto R^2$), of course, needs correction. This result was obtained based on the poor data of the PSD of the IMF for the period before 1966. Generally data of the PSD of the IMF show that (e.g. Burlaga, 1995) the exponent ν of PSD of the IMF does not tend to zero for the frequency less than 10^{-7} Hz of the IMF turbulence. So, averagely, a dependence $K \propto R^2$ is expected for the energy greater than 100 GeV.

QLT has undergone revision and development, especially during last 10–15 years. Bieber et al. (1994) found good agreement between theoretical results and observations, which was confirmed by Droge (2003) assuming the composite slab/two-dimensional model for turbulence geometry. Matthaeus et al. (2003) proposed a Nonlinear Guiding Center (NLGC) theory. This model includes the influence of parallel scattering and dynamical turbulence. Shalchi et al. (2004) presented a weakly nonlinear theory (WNLT) being a nonlinear extension of QLT. Recently, Qin (2007) developed a nonlinear parallel diffusion theory (NLPA) and demonstrated that the combination of the new NLPA and NLGC theories shows good agreement. In general, the significant differences between the expected results from the QLT on the one hand, and the expected results from the NLGC theory (Matthaeus et al., 2003) and WNLT (Shalchi et al., 2004) on the other, were found for the energy of the GCR particles up to few hundred MeV. For the energy > 1 GeV all theories (QLT, NLGCT and WNLT) give the same results (Droge, 2003; Shalchi and Schlickeiser, 2004). So, for the energy of the GCR particles 5–50 GeV, to which neutron monitors and ground muon telescopes respond, the QLT approach is acceptable i.e. that $\alpha = 2 - \nu$; then the relationship between the exponents γ and ν ($\gamma \approx 2 - \nu$), found for 11-year GCR variation in Alania and Iskra (1995); Alania et al. (2008); and for Fd in Wawrzynczak and Alania (2005, 2008) should be valid.

In this paper our aim is threefold: (1) to study the rigidity spectrum of the Fd of the GCR intensity using neutron monitors and ground muon telescopes experimental data, (2) to develop new 3-D time dependent model of Fd based on the Parker's transport equation, and (3) to establish a relationship between the rigidity spectrum of the Fd of the GCR intensity and PSD of the IMF.

3 Experimental data

We study Fd 2004, 6–20 November related with the series of the solar flares in period of 4–10 November having resulted in shocks waves and CME (ftp://ares.nrl.navy.mil/pub/lasco/halo). We use daily average data of the 22 neutron monitors (Alma-Ata, Apatity, Athens, Calgary, Climax, Haleakala, Irkutsk, Jungfraujoch, Kergelungen, Kiel, Larc, Lomnicky Stit, McMurdo, Mexico, Moscow, Oulu, Potchefstroom, Roma, South Pole, Tbilisi, Thule, Yakutsk) and 13 channels of Nagoya muon telescope (N0VV, N1WW, N1SS, N1EE, N1NN, N3EE, N3NN, N3SS, N3WW, N4NE, N4NW, N4SE, N4SW). Our aim is to find temporal changes of the rigidity dependence of the Fd. In connection with this to increase reliability of the calculations we use neutron monitors and muon telescopes data smoothed over 3 days. As an example, 3 days smoothed data of neutron monitors Calgary, Kiel and Nagoya N0VV muon telescope are presented in Fig. 1 (upper panel). The exponent γ of the power law rigidity spectrum was found using the expression (Dorman, 2004):

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

Where $R_{\max}$ is a rigidity beyond which the Fd of the GCR intensity vanishes. The method of calculation is described in papers eg. Wawrzynczak and Alania (2005, 2008). The

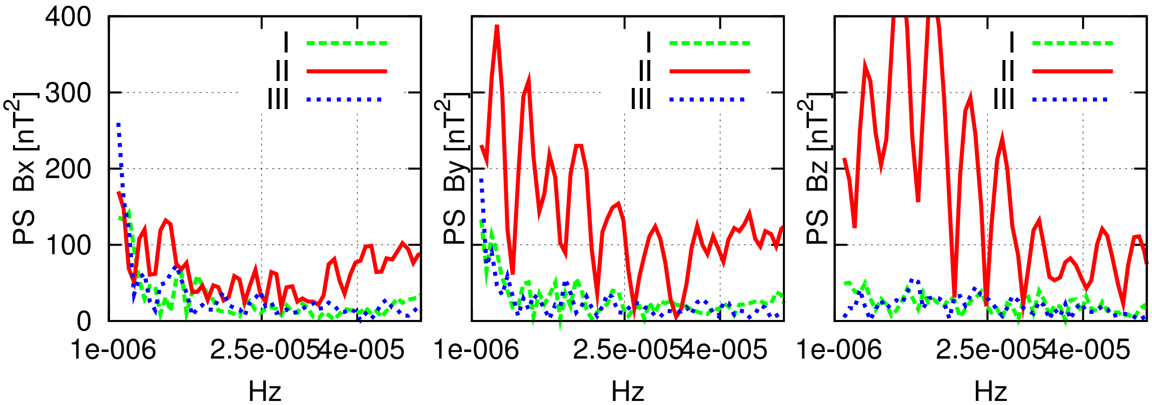

Fig. 2. Power Spectra of the Bx, By and Bz components of the IMF for the periods before (I), during (II) and after (III) the Fd in November 2004.

Table 1. The values of the exponent ν of the PSD of the IMF's components Bx, By and Bz for periods: before the Fd (I), during (II) and after (III) the Fd

IMF components	Exponent ν of the PSD of the IMF **I** period 24 Oct - 6 Nov	**II** period 7 - 20 Nov	**III** period 21 Nov -4 Dec
Bx	1.48 ± 0.05	1.51 ± 0.05	1.80 ± 0.07
By	1.48 ± 0.05	1.63 ± 0.05	1.50 ± 0.05
Bz	1.42 ± 0.05	1.83 ± 0.05	1.50 ± 0.05

temporal changes of the exponent γ were calculated using above mentioned all 22 neutron monitors and Nagoya muon telescopes data (13 channels). We take $R_{\max} = 100$ GV, considering that beyond 100 GV the Fd of the GCR intensity vanishes. To demonstrate validity of our assumption the temporal changes of the exponent were calculated for two values of $R_{\max} = 100$ GV and $R_{\max} = 200$ GV; results are presented in Fig. 1 (bottom panel). It is seen that there is not any difference in scope of accuracy of calculations for $R_{\max} = 100$ GV and $R_{\max} = 200$ GV. Figure 1 shows that rigidity spectrum for the beginning and recovery phases of the Fd is relatively soft ($\gamma_{100} \approx 1.03 \pm 0.25$, $\gamma_{200} \approx 1.11 \pm 0.27$) with respect to the rigidity spectrum in the minimum and near minimum phases of the GCR intensity ($\gamma_{100} \approx 0.75 \pm 0.18$, $\gamma_{200} \approx 0.83 \pm 0.20$). The temporal changes of the rigidity spectrum exponent γ 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 increases of the exponent ν of the PSD in the energy range of the IMF turbulence ($10^{-6} \div 10^{-5}$ Hz). We assume that the increase of the exponent ν during the Fd is generally caused by the creation of new, relatively large scale irregularities, i.e. a power of the PSD preferentially should be increased in the lower frequency part of the range $\sim 10^{-6} \div 10^{-5}$ Hz of the IMF turbulence (Wawrzynczak and Alania, 2005, 2008). The new created large scale irregularities can be connected with scattering of the convected structure of the IMF (E. Marsch, private discussion) or/due to the nonlinear interaction of high speed disturbances with the background solar wind in the interplanetary space.

To confirm a supposed relation of γ with ν there is necessary to find 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). For this purpose there is needed the definite length of the data series (about 20 days) to cover the frequency range of $f \sim 10^{-6} \div 10^{-5}$ Hz, being responsible for scattering of 5–50 GV rigidity particles of GCR. Unfortunately, it is not possible, because the length of data series is predetermined by the duration of Fd. For comparison we consider three periods: 24 October – 6 November before (I), 7–20 November during (II) and 21 November – 4 December after (III) the Fd. As mentioned above, lengths of data series for I and III periods are predetermined by the duration of Fd (length of the II period). The exponents ν of the PSD of the Bx, By and Bz (in GSE coordinate system) components of the IMF were calculated using hourly data of IMF from ACE (www.srl.caltech.edu/ACE/) and are presented in Table 1. Table 1 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). Intensification in the power of the IMF turbulence during the Fd is visually evident from the Power Spectrum (PS) of the IMF, especially for the By and Bz components, determining two-dimensional structure of the turbulence geometry (Fig. 2). Certainly, the obtained results are very averaged connected with the problem of the calculation of the exponent ν. As far we use Parker's transport equation (Parker, 1965) to describe long period (11-year) and short period (Forbush effects) variations, a relationship between γ and ν found for the long period (Alania and Iskra, 1995); Alania et al. (2008) should be extended for the short period, too. Thus, we can suppose that the relation (Wawrzynczak and Alania, 2005, 2008) between the exponent ν of the PSD of the IMF turbulence and the exponent γ of the rigidity spectrum of the Fd (when the ν increases the γ decreases) is related with the changes of the IMF turbulence during the Fd.

4 Model of the Forbush decrease

To describe the Fd of the GCR we use the Parker's transport equation (Parker, 1965):

$$\frac{\partial N}{\partial t} = \nabla_i(K_{ij}\nabla_j N) - \nabla_i(U_i N) + \frac{1}{3}\frac{\partial}{\partial R}(NR)(\nabla_i U_i) \quad (2)$$

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. The size of the disturbed vicinity where the Fd take place equals ~ 6 astronomical unites (AU). Size of modulation region equals ~ 30 AU, which is 5 times greater than the vicinity responsible for the Fd. This vicinity is restricted in heliolongitudes, heliolatitudes and distance as: $\varphi \in (140°, 220°)$ and $\theta \in (60°, 120°)$, $r \leq 6$ AU, the solar wind velocity is constant and equals $U = 400$ km/s. Our aim is to confirm by numerical solution a relation of the expected rigidity spectrum exponent γ of the Fd with the exponent ν of the PSD of the IMF turbulence. For this purpose in the change of the parallel diffusion coefficient $K_\parallel$ presented as $K_\parallel = K_0 K(r) K(R,t)$, we assume:
$K(R,t) = R^{\alpha(t)} = R^{2-\nu(t)}$,
$\nu(t) = 0.8 + 15(\frac{7t-0.7}{3})^{1.5}\exp(-8(t-0.1))$,
$K_0 = 4.5 \times 10^{21}$ cm^2/s,
$K(r) = 1 + 0.5(\frac{r}{1\mathrm{AU}})$
here r is heliocentric distance, t-time. The normalized parallel diffusion coefficient $K_\parallel = K_0 K(r) K(R,t)$ equals 10^{23} cm^2/s for 10 GV at Earth orbit; perpendicular and drift diffusion coefficients have a standard form (Wawrzynczak and Alania, 2008). Changes of the relative density and the calculated expected power law $R^{-\gamma}$ rigidity spectrum exponent γ of the Fd are presented in Fig. 3a,b, respectively. Also, the assumed temporal changes of the exponent ν of the PSD of the IMF turbulence is presented in Fig. 3b. We see that the simulated Fd (Fig. 3a) satisfactorily describes the experimental data (Fig. 1), and there is an inverse dependence between the changes of the exponent γ and the exponent ν (Fig. 3b), as we expected according to the assumption.

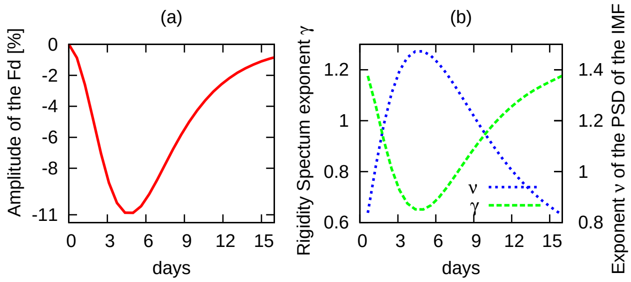

Fig. 3. **(a)** Changes of the expected amplitudes of the Fd of the GCR intensity for the rigidity of 10 GV based on the solutions of the transport equation for the Fd; **(b)** Temporal changes of the expected rigidity spectrum exponent γ based on the solutions of the transport equation for the Fd and the exponent $\nu(t)$ of the PSD of the IMF turbulence

5 Conclusions

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 $10^{-6} \div 10^{-5}$ Hz range of IMF turbulence.
2. The relation of the exponent γ with 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 QLT $\alpha = 2 - \nu$ (for $R \geq 1$ GV).
3. The rigidity spectrum exponent γ of the Fd can be used to estimate an exponent ν for the arbitrary period, which is not achievable by the in situ measurements of the IMF.
4. The proposed time dependent three dimensional model reasonably describes the behavior of the exponent γ during the Fd, being compatible with the experimental data.

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