Energy dependence of the rigidity spectrum of Forbush decrease of galactic cosmic ray intensity

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Abstract: We show that rigidity spectrum of Forbush decrease (Fd) of the galactic cosmic ray (GCR) intensity in September 9-23, 2005 has a clear dependence on the energy. We calculated rigidity spectrum of the Fd based on the data of the neutron monitors and Nagoya muon telescope channels divided in three groups according to their cut off rigidities. We find that temporal changes of the rigidity spectrum exponent $\gamma$ are approximately similar for all cut off rigidities, but values of $\gamma$ are the larger the higher are cut off rigidities. We conclude that rigidity spectrum of Fd is hard for lower energy range and is soft for the higher energy range. We believe that an energy dependence of the power law rigidity spectrum of Fd is observed owing to the preferential convection-diffusion mechanism of Fd in September 9-23, 2005. It is a reflection of role of the exponent $\nu$ of the power spectral density (PSD) of the interplanetary magnetic field (IMF) in formation of the dependence of the amplitudes of Fd on rigidity of GCR particles, meaning a manifestation of the role of $\nu$ in creation of the character of the rigidity spectrum. The exponent $\nu$ is greater for high frequency region of the IMF turbulence (responsible for scattering of low rigidity particles of GCR), than for low frequency region of the IMF turbulence (being responsible for scattering of higher rigidity particles). Based on the distribution of average turbulence energy among the IMF's components we challenge to estimate an existence of slab/2D structure of solar wind turbulence during the Fd in September 9-23, 2005.

Keywords: Forbush decrease, galactic cosmic ray intensity, rigidity spectrum, interplanetary magnetic field turbulence.

1 Introduction

The Forbush decreases (Fds) are called occasional decreases in the galactic cosmic ray (GCR) intensity during one-two days (as observed on Earth) followed by its gradual recovery in 5-7 days [1]. The Fds go after flares on the Sun and intensive solar coronal mass ejecta (CME) [2,3]. These phenomena appear randomly in time, sporadically without any regularity, increasing its frequency in ascending and descending phases of solar sunspot cycle. One of the fundamental characteristics of Fd is a dependence of amplitude (the difference between the GCR intensity at the onset and the minimum point of Fd) on the rigidity $R$ of GCR particles. Generally rigidity spectrum of Fd is found based on the values of amplitudes of Fd calculated for minimum point of the GCR intensity. However, to study the rigidity dependence of the Fd only based on the rigidity spectrum for the one time-point of the Fd is not sufficient to analyze dynamics of Fd. The time evolution of the rigidity spectrum of the Fd was studied by [4-9]. They showed that rigidity spectrum $\delta R(R)/R \propto R^\gamma$ of the great 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 high ($\gamma \approx 1 \pm 1.6$) at the beginning phase of the Fd, then it is gradually decreases up to the minimum (or near minimum) of the GCR intensity ($\gamma \approx 0.2 \pm 0.6$) to increase again during the recovery phase of the Fd.

It was showed for the 11-year variation [10-12] and for the Fds [5-9] of the GCR intensity that features of the temporal changes of the power law rigidity R spectrum $\delta R(R)/R \propto R^\gamma$ found by data of neutron monitors and Nagoya ground muon telescopes are related with the
change of the power spectral density (PSD) of the interplanetary magnetic field (IMF) turbulence (PSD \( \propto f^{-n} \), \( f \) is a frequency). Namely, changes of the exponent \( \gamma \) of the power law rigidity R spectrum \( \delta D(R)/D(R) \propto R^{-\gamma} \) explicitly depend on the changes of the exponent \( \nu \) of the PSD in the range of frequency \( f \approx 10^{-6} \div 10^{-5} \) Hz of the IMF turbulence, to which neutron monitors and ground muon telescopes respond. One of features in the changes of the rigidity spectrum of the 11-year variation of the GCR was recognition of a tendency of a rigidity dependence of the exponent \( \gamma \) [10]. According to quasi linear theory (QLT) [13-16] rigidity dependence of exponent \( \gamma \) is expected because of relation of parallel diffusion coefficient \( K \) on rigidity \( R \) as, \( K \propto R^{2-\nu} \), with the exponent \( \nu \) of the PSD of the IMF turbulence. To reveal rigidity dependence of \( \gamma \) is a difficult task for Fd due to its complexity. Nevertheless, in case when a convection-diffusion approximation is adjustable to describe Fd, there is expected a rigidity dependence of exponent \( \gamma \). We assume that from this point of view, one of suitable events is Fd in September 9-23, 2005.

2 Data analysis

The Fd in September 9-23, 2005 was previously analyzed in paper [9]. We have showed that the rigidity spectrum of the Fd is soft at the beginning of the Fd (\( \gamma \approx 1.49 \pm 0.34 \)) then it gradually hardens during the decreasing phase of the Fd (\( \gamma \approx 0.58 \pm 0.14 \)) and slowly softens (\( \gamma \approx 1.72 \pm 0.42 \)) in the recovery phase of the Fd. Moreover, we have provided the analysis of the IMF’s turbulence and presented that during the Fd we indeed observe the postulated increase of the exponent \( \nu \) of the PSD of the IMF in compare with the period before and after the Fd.

In this paper we analyze the Fd in September 9-23, 2005 in more detail using data of 17 neutron monitors and 5 channels of Nagoya muon ground telescope.

The following table lists the neutron monitor stations and Nagoya ground muon telescope channels used in calculation of the rigidity spectrum of the Fd in September 9-23, 2005.

<table>
<thead>
<tr>
<th>Group 1 Low cut off rigidity</th>
<th>Group 2 Moderate cut off rigidity</th>
<th>Group 3 High cut off rigidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station</td>
<td>Cut off rigidity [GV]</td>
<td>Station</td>
</tr>
<tr>
<td>Apatity</td>
<td>0.65</td>
<td>Climax</td>
</tr>
<tr>
<td>Calgary</td>
<td>1.09</td>
<td>Jungfraujoch</td>
</tr>
<tr>
<td>Cape Shmidt</td>
<td>0.45</td>
<td>Lomnitski Stit</td>
</tr>
<tr>
<td>Climax</td>
<td>3.03</td>
<td>Rome</td>
</tr>
<tr>
<td>Irkutsk</td>
<td>3.66</td>
<td>Tbilisi</td>
</tr>
<tr>
<td>Kiel</td>
<td>2.29</td>
<td>Nagoya N1EE</td>
</tr>
<tr>
<td>Oulu</td>
<td>0.81</td>
<td>Nagoya N1SS</td>
</tr>
<tr>
<td>Fort Smith</td>
<td>0</td>
<td>Nagoya N1NN</td>
</tr>
<tr>
<td>Yakutsk</td>
<td>1.70</td>
<td>Nagoya N1WW</td>
</tr>
</tbody>
</table>

Table 1: Neutron monitor stations and Nagoya ground muon telescope channels used in calculation of the rigidity spectrum of the Fd in September 9-23, 2005.
Figure 2: Temporal changes of the rigidity spectrum exponent $\gamma$ for period of September 10-18, 2005 based on the data of the stations divided in three groups according to their cut off rigidities: (1) for low, (2) moderate, and (3) high cut off rigidities.

The daily average amplitudes $J_i^k$ of the Fd for ‘i’ detector (neutron monitor or muon telescope) were calculated, as: $J_i^k = (N_i - N_0)/N_0$; $N_i$ is the running daily average count rate ($k=1,2,3,\ldots$ days) and $N_0$ is the 3 days average count rate before the Fd

The method of calculation is described in papers [6, 8]. With this method we calculated the rigidity spectrum exponent $\gamma$ of Fd for each day of September 9-23, 2005.

Figure 2 presents temporal changes of rigidity spectrum exponent $\gamma$ ($k=1,2,3,\ldots$ days) calculated based on the data of the neutron monitors and Nagoya muon telescope channels divided in three groups according to their cut of rigidities: (1) for low, (2) moderate, and (3) high cut off rigidities (Table 1). To cover a large range of cut of rigidities data some neutron monitors are included in two groups.

Figure 2 shows that temporal changes of $\gamma$ are approximately similar for all cut off rigidity groups, but values of $\gamma$ are the larger the higher are cut off rigidities. So, rigidity spectrum is hard for lower energy range and is soft for the higher energy range. Actually, it is a reflection of role of the exponent $\nu$ of the PSD of the IMF in formation of the dependence of the amplitudes of Fd on rigidity of GCR particles, i.e. a manifestation of the role of $\nu$ in creation of the character of the rigidity spectrum [5-12]. In order to confirm an idea that a peculiarity of $\gamma$ is related with the changes of the exponent $\nu$ of the PSD of the IMF turbulence, we carry out spectral analyzes of hourly data of the $B_x$, $B_y$, and $B_z$ components of the IMF, in the period September 10-23, 2005, for two frequency intervals, the first - I, $[2.5 \times 10^{-6} \text{ Hz}, 1.92 \times 10^{-5} \text{ Hz}]$, and the second one - II- $[1.42 \times 10^{-5} \text{ Hz}, 7.45 \times 10^{-5} \text{ Hz}]$.

Results of calculation are presented in Fig.3. Fig.3 shows that for the $B_x$ component an exponent $\nu$ is slightly differs for both intervals ($\nu_x(I) = -1.85 \pm 0.23$ and $\nu_x(II) = -1.66 \pm 0.16$), while for $B_y$ and $B_z$ components there are found various values of $\nu$. For $B_y$ we obtained $\nu_y(I) = -1.29 \pm 0.15$, and $\nu_y(II) = -2.04 \pm 0.14$; and for $B_z$: $\nu_z(I) = -1.16 \pm 0.13$, and $\nu_z(II) = -2.22 \pm 0.13$.

Taking into account the average, for the considered period (September, 10-23), solar wind velocity $V=600 \text{ km/s}$ and the IMF magnitude $B=5 \times 10^{-5} \text{ Gs}$ the lower frequency range I is responsible for modulation of the GCR particles with rigidities $\leq 60 \text{ GV}$ and higher frequency range II for modulation of the GCR particles with rigidities $\geq 15 \text{ GV}$ [18].

Figure 3: Power Spectrum Density of the $B_x$, $B_y$ and $B_z$ components of the IMF (from ACE) for the period September 10-23, 2005 and the exponents $\nu$ for the two frequency ranges I- $[2.5 \times 10^{-6} \text{ Hz}, 1.92 \times 10^{-5} \text{ Hz}]$;
So, there are observed changes of $v$ according to QLT; namely, $v$ is greater for high frequency region of the IMF turbulence (responsible for scattering of low rigidity particles of GCR), than for low frequency region of the IMF (being responsible for scattering of higher rigidity particles). It is worth to mention about the challenge to determine a character of turbulence during the Fd in September 9-23, 2005.

A central role in diffusion of GCR particles belongs to the character of IMF’s turbulence. We calculated average energy of turbulence for each $B_x$, $B_y$, and $B_z$ components of the IMF during a minimum and recovery phases of Fd (September 10-23, 2005). Results of calculation are presented in Table 2.

<table>
<thead>
<tr>
<th>IMF component</th>
<th>Contribution in the average energy of turbulence</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_x$</td>
<td>22.22%</td>
</tr>
<tr>
<td>$B_y$</td>
<td>38.77%</td>
</tr>
<tr>
<td>$B_z$</td>
<td>39.01%</td>
</tr>
</tbody>
</table>

Table 2: Contribution of the IMF’s components in the average energy of turbulence in the frequency range $[2.5 \times 10^{-6} \text{ Hz}, 7.45 \times 10^{-5} \text{ Hz}]$ for the period of September 10-23, 2005

Table 2 shows that ~ 80% energy of turbulence falls to the $B_y$ and $B_z$ components. We believe that this distribution of turbulence energy among IMF’s components supports that a turbulence of the IMF for period of September 10-23, 2005 has a slab/2D [19] character with contribution of $B_x$ with respect $B_y$ and $B_z$ components as, 20%/80%

3 Conclusions

1 We show that for minimum and recovery phases of the Fd in September 9-23, 2005, there is observed clearly established dependence of the exponent $\gamma$ of the rigidity spectrum $\delta R/D(R) \propto R^{\gamma}$ of the Fd on the rigidity of GCR particles registered by neutron monitors and Nagoya ground muon telescope.

2 The rigidity spectrum exponents $\gamma$ are the larger the greater are cut off rigidities of stations used in calculations, i.e. rigidity spectrum of the GCR intensity variations during Fd is hard for lower energy range and is soft for the higher energy range.

3 Despite Fd of the GCR intensity is very complex phenomenon, there is possible to reveal some events of Fd for which a minimum and recovery phases can be described by convection-diffusion approximation. In this case the QLT is valid and is possible to reveal rigidity dependence of the rigidity spectrum on the GCR particles rigidity, for rigidity range to which neutron monitors and ground muon telescopes respond.

4 We challenge to estimate an existence of slab/2D structure of solar wind turbulence during the Fd in September 9-23, 2005.

5 Acknowledgments

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6 References