Rigidity spectrum of Forbush decrease calculated by neutron monitors data corrected and uncorrected for geomagnetic disturbances

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Abstract. Forbush decreases (Fd) of the galactic cosmic ray (GCR) intensity and geomagnetic storms are observed almost at the same time. Geomagnetic storm is a reason of significant disturbances of the magnetic cut off rigidity causing the distortion of the time profile of the Fd of the GCR intensity. We show some differences in the temporal changes of the rigidity spectra of Fd calculated by neutron monitors experimental data corrected and uncorrected for the changes of the geomagnetic cut off rigidity. Nevertheless, the general features of the temporal changes of the rigidity spectrum of Fd maintain as it was found in our previous investigations. Namely, at the beginning phase of Fd rigidity spectrum is relatively soft and gradually becomes hard up to reaching the minimum level of the GCR intensity; then the rigidity spectrum gradually becomes soft during the recovery phase of Fd. We also confirm that for the established temporal profiles of the rigidity spectrum of Fd a structural changes of the interplanetary magnetic field turbulence in the range of frequencies, $10^{-6}$-$10^{-5}$ Hz are responsible.

1. Introduction
Geomagnetic disturbances and Forbush decreases (Fds) of galactic cosmic ray (GCR) intensity have a common origin in interplanetary space, however, the magnitudes of geomagnetic disturbances and Fds are not proportional to each other [1,2]. During geomagnetic storm a ring current is formed at the several earth radii causing a large reduction of the geomagnetic field [3]. These reductions are measured by the Dst index [4] (disturbance storm time index). Measurements of Dst and Fds indicate some unity in their interplanetary sources, however, a significant differences occur in the evolution of each one [5]. The most important difference is that Fds are governed by the electro-magnetic conditions in a large vicinity of the heliospheric region, while Dst variation describes only local situation in the Earth’s magnetosphere. The GCR intensity decreases along with the simultaneous changes in Dst index within 1982-2002 years were analyzed in [6], there was shown that the relation between GCR flux and geomagnetic activity is complex. The relationship between the Fds and the Dst index for the several Fds in cycle 23 was analyzed in [2]; there was shown a valuable negative correlation between Dst and Fd.
One of the fundamental uniqueness of Fd is a rigidity spectrum characterizing a rigidity dependence of the amplitudes of Fd. However, to analyze dynamics of Fd by one time-point, as it is generally accepted, is not sufficient. The time evolution of the rigidity spectrum of the Fd calculated by neutron monitors (NM) and muon telescopes experimental data was studied in [7], and references therein. They have shown that the power rigidity R spectrum \( \delta D(R)/D(R) \propto R^{-\gamma} \) for the great majority of the Fds at the beginning phase is soft \( (\gamma \approx 1.0 - 1.2) \), then gradually becomes hard \( (\gamma \approx 0.5 - 0.7) \) during the decreasing and minimum phases of Fd, and then steadily becomes soft in the recovery phase \( (\gamma \approx 0.8 - 1.3) \). They also have found that the temporal changes of the exponent \( \gamma \) are related with the changes of the exponent \( \nu \) of the power spectral density (PSD) of the IMF turbulence \( \text{PSD} \propto f^{-\nu}, f \text{ is a frequency} \), as \( \gamma \approx 2 - \nu \) in the range of frequencies \( f \sim 10^{-6} - 10^{-5} \text{ Hz} \) of the IMF turbulence, to which NM and muon telescopes respond. This relationship between the exponents \( \gamma \) and \( \nu \) is expected owing to the dependence of the diffusion coefficient \( K_{II} \) of GCR particles on the rigidity \( R, K_{II} \propto R^\alpha \), where according to the quasi linear theory \( \alpha = 2 - \nu \) [8].

It is apparent that data of NM are disturbed due to changes of the vertical geomagnetic cut off rigidity \( R_c \) directly related with the geomagnetic disturbances. So, it is natural to expect that the rigidity spectrum of the Fd of the GCR intensity will be distorted, as well.

The main purpose of this paper is threefold: (1) to calculate changes of the geomagnetic cut off rigidities for various NM stations during four Fds by the spectrographic global survey (SGS) method, and corresponding corrections of the amplitudes of Fd, (2) to settle on a relationship between changes of the geomagnetic cut off rigidities and Dst variations and then to find a reliable average coupling function between Dst and changes of the GCR intensity \( \Delta J[\%] \), and (3) to estimate how the change of the cut off rigidities of various NM stations influence on the temporal changes of the power rigidity spectrum of the Fd.

2. Experimental data and methods.
We analyze the largest four Fds of the 23rd solar cycle: I Fd, July, 6-30, 2000; II Fd, October, 19 – November, 11, 2003; III Fd, November 4-20, 2004; and IV Fd, September 6-23, 2005. During these Fds were observed significant geomagnetic disturbances affecting the vertical geomagnetic cut off rigidity \( R_c \) and, correspondingly, the level of the GCR intensity registered by NM stations. To calculate changes of cut off rigidity \( \Delta R_c \) during this Fds we have used SGS method [9,10]. Results of calculations of \( \Delta R_c \) and \( \Delta J[\%] \) for days of the minimum intensity of the four considered Fds are presented in figure 1.

Figure 1. The changes of geomagnetic cut off rigidities \( \Delta R_c [\text{GV}] \) (dots) and intensities \( \Delta J[\%] \) (triangles) vs. the geomagnetic cut off rigidity \( R_c \) at the minimum points of intensity for four Fds

Figure 1 shows that distributions of the changes of geomagnetic cut off rigidities \( \Delta R_c \) approximately have an identical character during the II and III Fds and reach minimums at 5-6 GV of \( R_c \). Similar tendency is observed during the I Fd, however, changes of \( \Delta R_c \) vs. cut off rigidity during IV Fd is reasonably different. It is clear, that each geomagnetic storm has a specific character due to different scenarios of interaction between the geomagnetosphere and disturbances in the interplanetary space. So, different complex structure of the Earth’s magnetic field during magnetic storms lead to the different changes of \( \Delta R_c \). Variation of the GCR intensity \( \Delta J[\%] \) caused by the changes of \( \Delta R_c \) are
presented in figure 1 (triangles), as well. One can find almost similar profiles of $\Delta J[\%]$ versus $R_c$ for all Fds. $\Delta J[\%]$ increases sharply in the range of $2\times6$ GV of $R_c$ and then gradually decreases. There is a question of interest, what is a level of correlation between $\Delta R_c$ and the geomagnetic index Dst on one hand, and between $\Delta J[\%]$ and Dst, on the other. The point is that in essence $\Delta R_c$ is calculated based on the GCR intensity changes measured by NM stations with different $R_c$ and should characterize an average state of the whole geomagnetosphere, while Dst generally gives an information about the vicinity of geomagnetosphere inside of ring current, which during geomagnetic storms can be extended not far than 8-10 earth’s radii.

Figure 2. The changes of the Dst index and the amplitude of GCR intensity correction $\Delta J[\%]$ for Climax, Hermanus, and Haleakala neutron monitor stations during four Fds.

One of our aims is to find whether or not it is possible to find a reliable average coupling function between Dst and $\Delta J[\%]$ caused by the changes of $R_c$. A possibility of creation of a coupling function between Dst and $\Delta J[\%]$ is based on the analyses of the high correlation and visibly well-established linear regressions of $\Delta J[\%]$ on Dst. For this purpose changes of Dst index and $\Delta J[\%]$ for Climax, Hermanus, and Haleakala NMs during four Fds we present in figure 2. Figure 2 shows that there are high correlations between Dst index and the amplitudes of the GCR intensity $\Delta J[\%]$ for all NMs during considered four Fds. To establish a quantitatively relationship between Dst and $\Delta J[\%]$ we found linear regression of $\Delta J[\%]$ on Dst. Figure 3 presents regressions lines of $\Delta J[\%]$ on Dst index based on the data of four Fds: crosses (+)-July 2000, circles (-)-October 2003, triangles (▲)-November 2004 and squares (◘)- September 2005 for Climax, Hermanus, and Haleakala NM stations. Based on analyses of the regression lines of $\Delta J[\%]$ on Dst one can recognize a possibility of estimation of $\Delta J[\%]$.

Figure 3. Regressions line of $\Delta J[\%]$ on Dst index based on the data of four Fds: crosses (+)-July 2000, circles (●)-October 2003, triangles (▲)-November 2004 and squares (◘)- September 2005 for Climax, Hermanus, and Haleakala NM stations.

3. Rigidity spectrum of the Forbush decrease
The power type rigidity R spectrum $\delta D(R)/D(R) \propto R^{-\gamma}$ was found by means of amplitudes of the corrected and uncorrected NM stations data. Amplitudes of the Fd were calculated with respect to the average intensity during 3 days before starting of Fd for each NM. To reveal average reliable temporal changes of the exponent $\gamma$ we have smoothed daily data over 3 days (left panel of figure 4). Then using the method described in detail in [7] we have calculated the exponent $\gamma$ for each day.
Results of calculations of $\gamma$ in September 2005 based on the data of NM: (1) uncorrected, (2) corrected for changes $\Delta R_c$, and (3) corrected for the geomagnetic disturbances by the relation between the Dst index and $\Delta J[\%]$ are presented in figure 4 (right panel).

Figure 4 shows some differences in the temporal changes of the exponents $\gamma$ found by: (1) uncorrected, (2) corrected for changes $\Delta R_c$, and (3) corrected for the geomagnetic disturbances Dst index data of NM. However, the general features of the temporal changes of the power law rigidity spectrum exponent $\gamma$ of Fd maintain as it was found in previous investigations [7], and references therein. Namely, at the beginning phase of Fd rigidity spectrum is relatively soft and gradually becomes hard up to reaching the minimum level of the GCR intensity; then during the recovery phase of Fd the rigidity spectrum gradually becomes soft. One can see that obtained exponent $\gamma$ (blue line) fits in scope of the error bars to the exponent $\gamma$ calculated based on the corrected GCR intensity. So, the relation between the Dst index and the $\Delta J[\%]$ can be used for the estimation of the rigidity spectrum exponent $\gamma$ taking into account the geomagnetic disturbances.

Figure 4. Temporal changes of the GCR intensity corrected and uncorrected for geomagnetic disturbances for Climax, Rome, and Haleakala NM stations; and temporal changes of the rigidity spectrum exponent $\gamma$ calculated based on the uncorrected and corrected data of NM in period of September 9-23, 2005.

4. Conclusion
The power law rigidity R spectrum ($\delta D(R)/D(R) \propto R^{-\gamma}$) of Fd found by neutron monitors data non corrected and corrected for geomagnetic disturbances are different, but character of profiles of temporal changes of the exponent $\gamma$ is almost similar. At the beginning phase of Fd rigidity spectrum is relatively soft and gradually becomes hard up to reaching the minimum level of the GCR intensity; then during the recovery phase the rigidity spectrum gradually becomes soft. We confirm that for the established temporal profiles of the exponent $\gamma$ during Fd are responsible the structural changes of the interplanetary magnetic field turbulence in the range of frequencies, $10^6-10^5$ Hz to which neutron monitors and muon telescopes respond. In some acceptable degree data of neutron monitor stations during Fd can be corrected for geomagnetic disturbances using the Dst index and by the same token avoiding an utilize of complex spectrographic global survey method.

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