Rigidity dependences of the main characteristics of Forbush decreases

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Abstract. Forbush decrease is an effect in the cosmic rays physics which manifests itself as a sudden depression of the intensity of cosmic rays. Active phase of Forbush decrease lasts for several days and is often accompanied by a geomagnetic storm. The reason for such sudden depressions originates from the Sun, and is connected with a phenomenon of solar physics known as coronal mass ejections. Nowadays Forbush decreases are mostly studied by ground based detectors such as neutron monitors and muon hodoscopes. These detectors are characterized by small statistical fluctuations but register secondary cosmic rays which are created in interactions of primary cosmic rays with Earth atmosphere. This work is based on the data obtained by the satellite experiment PAMELA. The main characteristics of Forbush decreases are calculated for a fluxes of cosmic rays protons in the rigidity range 0.8 – 9 GV.

1. Introduction
Forbush decreases (FD) were discovered by S. E. Forbush in 1937 [1]. FD is a reaction of cosmic radiation on the propagation of coronal mass ejections in the interplanetary space [2], which is also known as interplanetary coronal mass ejection (ICME). A huge amount of solar plasma and accompanying magnetic field is thrown outwards from the Sun corona during coronal mass ejections. The basic structure of classical ICME consists of shock wave, sheath region and ejecta parts. The shock wave is the first high speed part of ICME and it originates from the explosive nature of the discussed effect. The sheath region is characterized by highly disturbed characteristics of the interplanetary medium, such as magnetic field and solar wind speed, created by the propagation of the shock wave. The ejecta is a last part of the ICME which is characterized by increased and fluctuations free interplanetary magnetic field and solar wind speed. Despite more than eighty years of increased scientific interest in this field, there is no clear understanding of the main mechanisms which are responsible for generation of FDs. The reasons for that can be divided into two categories. The first one is strongly related to the complexity of the effect itself. CMEs range from huge (∼10^{13} kg) high speed events (∼2000 km s^{-1}) to small and slow releases of solar plasma with no distinct effect on cosmic ray particles in interplanetary space. More over FD properties may be changed due to observer position related to ICME [3]. The second one is connected with technical limitations of the current scientific equipment in terms of studying FDs.

Nowadays FDs are mostly studied by ground based detectors such as neutron monitors and muon hodoscopes, which register so-called secondaries which are produced by interactions of primary CRs with Earth atmosphere. The effective rigidity for the most part of such detectors is ∼ 10 GV, whereas the main part of the studied effect is obtained from the low energy region of the CR particles. Satellite
detectors operate with the primary cosmic rays but the complexity of the studied effect needs a huge amount of scientific data to be gathered with the limited number of available apparatus.

2. PAMELA experiment
Current work is based on the data obtained by the PAMELA experiment, which was launched onboard the Resurs DK-1 satellite in June 2006 and has been operated for 10 years. PAMELA spectrometer consists of time of flight system, magnetic spectrometer, electromagnetic calorimeter, anticoincidence systems and neutron detector [4, 5]. Spectrometer PAMELA was designed to provide measurements of the fluxes of the different cosmic ray particles in the energy range from several hundreds of MeV to several hundreds of GeV with unprecedented precision.

3. Data analysis
Amplitude and recovery time of Forbush decreases are basic properties of the studied effect. These characteristics describe the main basic part of the modulation process of FDs, and implicitly characterize the total amount of the disturbance at the measurement point. Some discussions on the rigidity behavior of this basic characteristic are still available in the scientific literature. Several investigations in these fields have concluded that there is no rigidity dependence of the recovery time of FDs [6, 7], others have found both types of the events with and without rigidity dependence of the recovery times [8, 9]. Also there are no average laws of rigidity dependence of amplitude and recovery time, which were calculated by primary CRs data. In this work we continue to analyze rigidity dependencies of the characteristics of FDs registered by the PAMELA experiment [10].

We begin this analysis with a FD which occurred in March 2013 during solar maxima. This event was caused by isolated halo CME occurred on March 15, 2013. FD generated by this CME was selected for the study according to basic properties of classical two step FD [11]. The time profile of the CR protons (R ∼ 1 ÷ 3 GV) of the discussed event is shown on figure 1. The amplitude of the decrease calculated with respect to the undisturbed conditions is ∼ 20%, which is almost four times bigger than for the same event obtained by the Oulu neutron monitor. The shock, sheath and ejecta regions are clearly identified from profiles of magnetic field, solar wind speed and proton temperature which are also shown. These characteristics of interplanetary space were taken from ACE science center [12]. Expected proton temperature was calculated by empirical dependence [13] and used as a selection criterion for ejecta identification. The technique of ICME stages identification is discussed in [14].

FD amplitude (A_{FD}) was calculated for 11 intervals of rigidity of CR protons between 0.8 ÷ 9 GV. Calculated rigidity dependence of amplitude versus rigidity was fitted by power ∼ bR^{-γ} and exponential ∼ ae^{-αR} laws. The results are shown on figure 2.
Figure 1. FD in the cosmic ray protons obtained by PAMELA ($R \approx 1 \div 3$ GV) and corresponding characteristics of disturbed interplanetary medium.

Recovery profiles of the fluxes of CR protons during selected FD were fitted by an exponential function $F = 1 - \Delta F_D \cdot \exp[(t - t_0)/\tau]$, with characteristic recovery time $\tau$, where $F$ is a normalized flux of CR protons, $t_0$ is FD start time. Obtained rigidity dependence of calculated recovery times is also fitted by exponential and power laws as for rigidity dependence of amplitudes. The results are shown on figure 3.

Figure 2. Rigidity dependence of FD amplitude for the event occurred in March 2013.
4. Conclusions

Rigidity dependences of amplitudes and recovery times of classical FD which occurred in March 2013 have been calculated using data on primary cosmic ray protons. All dependencies were fitted by means of power and exponential laws and both of them suggested applicable for that purpose \((\chi^2_{\text{exp}} \sim \chi^2_{\text{power}})\). Power law index \(\gamma\) for dependence of amplitudes was found to be equal 0.28, whereas earlier studies of such dependencies suggested that index to be in the range of \(\gamma \approx 0.4 \div 1.2\) [11]. Clear rigidity dependence of FD recovery time was found. It may be suggested that recovery times of classical FD generated by strong halo CMEs are rigidity dependent. More FDs will be analysed in the future which allow to derive averaged laws of this rigidity dependencies of amplitude and recovery times, which will be acceptable for theoretical models. Also non classical FDs will be analysed to understand why some previous studies did not find rigidity dependence of recovery time of FDs.

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