On recurrent Forbush Decreases

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Abstract. The methods of nonparametric and multivariate statistics were used to study features of recurrent Forbush decreases (FDs) and to compare them with sporadic ones. The FEID database created and maintained in IZMIRAN allowed us to distinguish isolated FDs caused by high-speed streams from coronal holes (350 events) and by interplanetary disturbances from coronal mass ejections (207 events). Distributions of all parameters turned out to be more compact and to have smaller medians for recurrent events than for sporadic ones. Comparison of distributions of FD magnitude for different groups of events suggested that most FDs were related to coronal holes during the minimum between solar cycles 23 and 24. Multiple correlation coefficients between FD parameters and a set of solar wind parameters revealed that recurrent FDs depend less strongly on the characteristics of interplanetary disturbances than sporadic ones.

1. Introduction

Forbush decreases (FDs) are the results of influence of solar wind (SW) disturbances on background cosmic rays (CR) [1, 2, 3]. A relatively fast CR density decrease (with the biggest and extremely variable CR anisotropy) followed by a slower recovery on a time scale of several days are observed during FD. There are two different kinds of FDs associated with two types of solar sources: recurrent FDs caused by high-speed streams (HSS) from coronal holes (CHs) and sporadic FDs caused by interplanetary disturbances (ICMEs) from coronal mass ejections (CMEs) [4].

In the case of CHs, the region of interaction between HSS and ambient SW is characterized by greater density and stronger and more variable interplanetary magnetic field (IMF). The distinctive features of the main part of HSS are its higher speed and temperature, low density and weaker IMF [5, 6]. The influence of HSS on CR modulation has been studied in many works [e.g. 7, 8]. Some studies compare different types of FDs using statistical methods based on large number of events [9, 10, 11]. However, one can note some shortcomings of this area of research such as selecting groups of events by indirect features and/or using data observed at small number of stations and/or describing FD only by one parameter (usually, variations of CR density). The objective of our work is to study properties of recurrent FDs and to compare them with sporadic FDs using methods of nonparametric and multivariate statistics provided by large amount of data. We used FD characteristics (variations of CR density and CR anisotropy) obtained by global survey method (GSM) on the data of about 40 neutron
monitors [12]. Recurrent and sporadic FDs were carefully selected with considering of various solar activity and interplanetary medium parameters [13].

2. Data and Methods

In this study we use the Forbush Effects and Interplanetary Disturbances (FEID) database (HYPERLINK “http://spaceweather.izmiran.ru/eng/dbs.html”) created and maintained in IZMIRAN. The database contains FDs parameters obtained from the data of worldwide neutron monitor network using GSM for particles with rigidity 10 GV. The FEID database also includes geomagnetic indices, SW parameters and solar geophysical data. The database contains more than 7000 FDs since 1957 (SW data since 1964). Our study of FDs associated with HSS from CHs assumes that each event is determined by a single solar source. We distinguished FDs created by only one source selecting the events with an onset no less 36 h prior to the next event and at least 60 h after the previous event (if the previous FD was greater than 1.4%). The next step – identification of recurrent and sporadic (for comparative analysis) FDs – required a joint analysis of interplanetary and solar data [13]. Analysis of SW parameters – velocity, density, temperature, IMF intensity – made it possible to refer FD to one of the two groups preliminary. Then the analysis of solar data was carried out which, as a rule but not always, confirmed the preliminary conclusions. At the last step, we compared the results to catalogs of CHs [14] and CMEs [15] and our conclusions mostly were confirmed. Since a confident identification of the event with a solar source requires complete and reliable data, then all selected recurrent FDs (CH group, 350 events) and sporadic FDs (CME group, 207 events) refer to the recent period (since 1997). We applied statistical analysis to study CR variations, geomagnetic activity and interplanetary disturbances in the CH group and to compare them with the CME group. To characterize each event, we used maximum (during the event) values: CR density variation (FD magnitude – $A_f$); absolute value of CR density hourly decrease (FD decrease rate – $D_{max}$); equatorial component of CR anisotropy ($A_{xy_{max}}$); range of north–south component of CR anisotropy ($A_{z_{range}}$); geomagnetic Ap index ($A_{p_{max}}$); absolute value of geomagnetic $Dst$ index ($|Dst_{min}|$); SW velocity ($V_{max}$) and IMF intensity ($B_{max}$). Statistical analysis of these parameters included: analysis of distributions; calculation of descriptive statistics and Pearson correlation coefficients; multiple linear regression analysis [16, 17].

3. Results and Discussion

Table 1 presents the results of calculation of medians, mean values and interquartile ranges (a distance between 25% and 75% quartiles of the distribution) for eight parameters in the CH and CME groups. For all parameters (except SW velocity) medians and interquartile ranges are significantly less for recurrent FDs than for sporadic ones. Despite the great differences in HSS from CHs, the CH group turned out to be more compact and uniform as to events associated with CMEs. Median of SW velocity is a little more in the CH group although maximum velocity has been observed in the CME group; the interquartile ranges are approximately equal in both groups of events.

Figure 1 presents histograms of SW velocity in the CH and CME groups. Curve lines represent lognormal (left) and normal (right) distributions. Calculation of Kolmogorov-Smirnov statistics [16] reveals that the distribution of SW velocity does not fit to any of these laws in the CH group and corresponds to lognormal law in the CME group. Calculated value of skewness is statistically insignificant for recurrent FDs and significantly positive for sporadic ones. The difference in the distributions of SW velocity for recurrent and sporadic FDs could be explained by the fact that many FDs are caused by ICMEs with low speeds, but the FDs from low speed “high speed streams” are observed rarely (because they need even lower speed of the ambient SW). Figure 2 presents histograms of FD magnitude in the CH and CME groups. Calculation of Kolmogorov-Smirnov statistics and skewness reveals that both distributions do not fit to normal/lognormal laws and are right-skewed. The distribution is peaked, skewed, compact for recurrent FDs and highly skewed with a long “tail” in the region of large values for sporadic FDs. Figure 3 presents complementary cumulative distribution functions (CCDF) of FD magnitude for the CH and CME groups and for the events observed in the minimum between solar cycles 23 and 24. We can see that the distribution of FD
magnitudes in the minimum are very close to the distribution of recurrent FDs. This can be explained by the predominance of FDs associated with CHs in the period of this minimum.

Table 1. Descriptive statistics for FD and SW parameters and geomagnetic indices (Med – median, IQR – interquartile range)

|          | CH                      | CME                      |
|----------|-------------------------|--------------------------|
| $A_F$, % | Med 1.1, Mean 1.22 ± 0.03, IQR 0.7, Min 0.4 | Max 3.6, Med 2.1, Mean 3.03 ± 0.18, IQR 0.3, Min 0.3, Max 13.8 |
| $D_{max}$ %/h | 0.25, Mean 0.27 ± 0.02, IQR 0.09, Min 0.11 | Max 1.02, Mean 0.41, Max 0.58 ± 0.04, Min 0.36, Max 0.12, Max 4.06 |
| $A_{xymax}$, % | 0.99, Mean 1.04 ± 0.02, IQR 0.35, Min 0.47 | Max 2.43, Mean 1.61, Max 1.79 ± 0.06, Min 0.88, Max 0.56, Max 5.26 |
| $A_{range}$, % | 0.97, Mean 1.01 ± 0.02, IQR 0.35, Min 0.53 | Max 2.52, Mean 1.76, Max 2.04 ± 0.08, Min 1.27, Max 0.53, Max 5.95 |
| $A_{max}$ | 27, Mean 33.2 ± 1.2, IQR 31, Min 1 | Max 154, Mean 48, Max 64.7 ± 4.43, Min 72, Max 300 |
| $|D_{zmin}|$ | 29, Mean 32.7 ± 1.04, IQR 21, Min 1 | Max 119, Mean 47, Max 64.4 ± 4.21, Min 61, Max 422 |
| $B_{max}$, nT | 11.2, Mean 11.7 ± 0.2, IQR 4.8, Min 4.3 | Max 24.9, Mean 13.8, Max 16.3 ± 0.65, Min 10.5, Max 4.7, Max 65.6 |
| $V_{max}$, km/s | 564, Mean 567 ±6, IQR 162, Min 331 | Max 907, Mean 492, Max 522 ± 9, Min 154, Max 327, Max 959 |

Figure 1. Histogram of SW velocity.  
Figure 2. Histogram of FD magnitude.

Pearson paired correlation coefficients between the parameters were calculated for the CH and CME groups; $z$–statistic was applied to estimate the significance of the difference between correlation coefficients. The correlation coefficients between SW velocity and IMF intensity in the CH group ($r = 0.52$) and in the CME group ($r = 0.55$) differ statistically insignificantly. For both groups of events, SW disturbances with larger velocity result stronger compression of interplanetary matter and IMF; for large ICMEs, the correlation between SW velocity and IMF intensity can exist already in the solar sources [4]. In the CH group, the correlations between FD magnitude and SW parameters are moderate ($0.3 \leq |r| < 0.5$) while the correlations between three other FD parameters and SW parameters – weak ($|r| < 0.3$) or statistically insignificant. In the CME group, the correlations between FD magnitude and SW parameters are high ($0.7 \leq |r| < 0.9$) while the correlations between the rest of FD parameters and SW parameters are noticeable ($0.5 \leq |r| < 0.7$). Thereby, the correlations between FD parameters and SW parameters are significantly weaker in the CH group than in the CME group. Significant positive
correlation between FD parameters and SW parameters is consistent with the findings of e.g., [4] that when SW disturbance moves with faster speed and the magnetic field is stronger in it, the greater decrease of CR density occurs during the main phase of FD. The results of the multiple regression analysis (presented below) show that the relationship between FD parameters and geomagnetic indices is completely determined by their common dependence on SW parameters (partial correlation coefficients between FD parameters and geomagnetic indices are statistically insignificant).

![Figure 3. Complementary cumulative distribution function of FD magnitude on a log–log scale.](image)

We estimated the dependence of FD parameters (predicted or dependent values) on the geomagnetic indices and SW parameters (a set of predictors) using multiple linear regression model [17]. The results are presented in table 2 for the dependent variables with confirmed (by F–test) overall statistical significance of linear regression model. In the CH group, the results are statistically significant only for FD magnitude and the multiple correlation coefficient indicates moderate correlation ($R=0.48$). We can see that the linear relationship of FD parameters on the predictors set much better corresponds to the observed data in the CME group: the multiple correlations are high for FD magnitude ($R=0.81$) and FD decrease rate ($R=0.78$) and noticeable for equatorial CR anisotropy ($R=0.61$). Standardized regression coefficients (or partial correlation coefficients) estimate a relative contribution of each predictor to the regression; only statistically significant coefficients are presented in table 2. The values of standardized regression coefficients in table 2 reveal that IMF intensity gives a larger part of contribution to the prediction of FD magnitude in the CH group. In the CME group, FD magnitude and FD decrease rate are predicted roughly equally by both SW parameters but equatorial CR anisotropy is predicted mostly by SW velocity. The results in table 2 also reveal that the multiple linear regression model gives statistically insignificant standardized regression coefficients for geomagnetic indices in both groups of events. We can conclude that both geomagnetic indices are related with CR density variations only through their common dependence on SW parameters.
Furthermore, geomagnetic activity is determined by the solar wind flowing around the Earth’s magnetosphere, while GCR modulation is a result of the influence of the whole large-scale interplanetary disturbance [4].

Table 2. Standardized regression coefficients and multiple correlation coefficients for multiple linear regression model: dependent variables – $A_F$, $A_{max}$, $A_{xy_{max}}$, $A_z_{range}$; predictors – $B_{max}$, $V_{max}$, $A_{p_{max}}$, $|Dst_{min}|$. Only statistically significant regression coefficients are presented in the table.

| Group of events | CH | CME |
|----------------|-----|-----|
| Standardized variable | | |
| $A_F$ | 0.38 | 0.46 |
| $A_{max}$ | 0.46 | 0.38 |
| $D_{max}$ | – | – |
| $A_{xy_{max}}$ | – | 0.37 |
| Multiple correlation coefficient | 0.48 | 0.81 |

Figure 4. Dependence of FD magnitude (%) on SW parameters in the CME group.

It is clearly visible at the contour plots of $A_F$ on the $(V_{max}, B_{max})$ plane (figure 4, 5) that the dependence of FD magnitude on SW parameters is much closer to the linear model in the CME group than in the CH group. On the contour plot for the CME group (figure 4), FD magnitude has minimum values for small $V_{max}$ and $B_{max}$ (the bottom left quadrant) and maximum values for the largest $V_{max}$ and $B_{max}$ (the upper right quadrant); the direction of FD magnitude gradient is almost unchangeable. The dependence of FD magnitude on SW parameters in the CH group is more complicated (figure 5). In this group, FD magnitude also has low values for small $V_{max}$ and $B_{max}$ and higher values for the largest $V_{max}$ and $B_{max}$. However, a number of local maxima are singled out, indicating the existence of anomalously large Forbush decreases related with not strongly perturbed SW. For example, the anomalously large for the CH group FD magnitudes (up to 3.6%) is associated with values of SW parameters in the mean–third of the ranges ($500 \text{ km/s} < V_{max} < 650 \text{ km/s}$, $11.5 \text{ nT} < B_{max} < 16.5 \text{ nT}$).

4. Conclusions.
The FEID database allowed to select isolated (non–overlapping) FDs and to associate part of them (since 1997) to SW disturbances from CHs (350 recurrent FDs) and CMEs (207 sporadic FDs). Large amount of data enabled to use statistical methods (distribution analysis, correlation analysis, multiple linear regression analysis and descriptive statistics) to describe the properties of recurrent FDs and to compare them with sporadic FDs.

The distributions of FD parameters and of maximum (during the event) values of IMF intensity and geomagnetic indices (Ap and $|Dst|$) are unimodal, peaked and right-skewed for recurrent FDs. These distributions are more compact and have smaller medians than corresponding distributions for sporadic FDs. SW velocity distribution is almost symmetrical for recurrent FDs and right-skewed for sporadic ones. This can be explained by the fact that many of observed FDs are caused by ICMEs with low speeds, but the FDs from low speed “high speed streams” are registered rarely. Comparison of FD magnitude distributions for recurrent FDs, sporadic FDs and FDs registered during the minimum between solar cycles 23 and 24 revealed that FDs were mostly caused by HSS from CHs during this minimum. It is assumed that this is true for most of the periods of low solar activity.

For recurrent FDs, the correlation between SW parameters and FD parameters is moderate ($0.3 \leq |r| < 0.5$) for FD magnitude and insignificant or weak ($|r| < 0.3$) for FD decrease rate and CR anisotropy. Corresponding correlations for sporadic FDs are significantly higher. Partial correlations between geomagnetic indices and FD parameters are statistically insignificant for both groups of FDs: the geomagnetic indices are related with CR density variations only through their common dependence on SW parameters.

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