Forbush-effects with sudden and gradual storm commencement

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Abstract: For overall studying of the Forbush-effects (FEs) database of transient phenomena in the cosmic rays and interplanetary space was created and is continuously updating. Various dependences of the FE size on the internal and external characteristics were examined and different groups of events were distinguished. Both recurrent (corotation of the high speed streams from the coronal holes) and sporadic (CMEs) events have been considered. The groups of events beginning with the Sudden Storm Commencement (SSC), and without shocks are allocated and studied. It is shown that derived FE magnitude dependences (on the interplanetary disturbance parameters, on the indices of geomagnetic activity etc.) are significantly different for these groups. Most likely these differences are caused by predominance of different kind of sources of the solar wind disturbance (CMEs or the coronal holes) in separated groups.

Keywords: cosmic ray variations, Forbush-effects, sudden storm commencement (SSC).

1 Introduction

Forbush-effect (FE), or Forbush decrease (FD), – is the change of cosmic ray (CR) density and anisotropy in the large scale disturbances of the solar wind (SW). This effect was discovered in 1937 [1], and since that time it was widely studied, for example, [2-7]. There are two main types of interplanetary disturbances [2,3,5,7]: caused by coronal mass ejection (CME) or high speed streams (HSS) from coronal holes. Both of them are able to produce FE. However, the mechanism of CR modulation in these two types of SW disturbances is different [2,7,8] as well as different the parameters of two types of the FEs, and it would be desirable to get quantitative data on this difference. But the problem is in an identification of the event with its solar source. Moreover many events have a mixed origin and may be caused both by CME and coronal holes.

In our study we divided all the FEs in two groups by the features of their onset: the events which have begun with arrival to the Earth of an interplanetary shock, and the events without shock. Of course, such a division doesn’t completely correspond to division on solar sources. Shocks at the Earth are sometimes observed on the fronts of coronal holes HSS. On the other hand, a lot of the interplanetary disturbances created by CME, i.e. ICME come without a shock. Nevertheless, it is possible to assert that shocks are more characteristic for events caused by CME and aren't typical for the events connected with coronal holes though this statement needs additional proofs and detailed study. Division of all magnetic storms into events with the gradual and sudden commencement is also applicable to FEs. In the present work the statistical analysis of a big amount of the data is performed to study a relation between various characteristics of the FE among themselves and with other parameters for two various groups: for events which have begun with arrival to the Earth an interplanetary shock (group S), and events with gradual onset, which weren’t accompanied nor by SSC, neither shock (group NS).

2 Data and methods

Variations of the CR density and anisotropy are combined with solar, interplanetary and geomagnetic parameters into database of interplanetary disturbances and Forbush-effects specially created in IZMIRAN [7,9]. Cosmic rays are presented there by results of global survey method (GSM) by the data of all world neutron monitor network calculated for rigidity 10 GV. Solar wind data are taken from OMNI database (http://omniweb.gsfc.nasa.gov). Now in database of FEs there are about 6000 events covering period 1957-2010. Database includes considerable the number of FE characteristics some of them are shown on figure 1. The database allows defining the various samples of interrelations between various parameters of events, representing the information in digital and in the graphic form that we use in the present work. Unfortunately, not all events are equally suitable for the statistical analysis. For example, if two solar wind disturbances follow one after another without a sufficient break the first FE hasn't time to develop, and the second one develops under influence two
disturbances. To avoid such interferences, we have chosen those events which beginning has been separated from next FE, at least, at 60 hours.

Figure 1. Typical behavior of the CR density in FE. $A_F$ – is a FE magnitude; $\Delta m_{min}$ – is a maximum CR density decrease per hour; $t_{min}$ – the duration of the main phase of FE between the onset and minimum of CR density.

As influence of small decreases, as a rule, insignificant, we left those events to which preceded FE, is less than 1.5 % in sample. The remained events have been divided on two groups: S (with interplanetary shocks) and NS (without shocks). The sudden storms commencement (SSC) was used as proxy of interplanetary shocks (ftp://ftp.ngdc.noaa.gov). The weakest and unreliable SSC – those that by magnetic observatories haven't been respected to class A (IAGA Bulletin), haven't been included in S-group. In certain cases the S-group joined events in which SSC were absent, but there were the shocks observed on the ACE satellite (http://www.swpc.noaa.gov/ace), Wind (http://lepmfi.gsfc.nasa.gov) and SOHO (http://lascowww.nrl.navy.mil). In result, S-group contains of 536 events, and NS-group - 2432.

3 Discussion of the results

In Table 1 the mean values of the FE characteristics and other parameters for S and NS groups are presented: $A_F$ – magnitude of the FE; $A_{ym}$ – equatorial and north-south components of the CR anisotropy; $\Delta m_{min}$ – maximum hourly decrease of the CR density; $\Delta m_{max}$, $D_{min}$ – extreme values of geomagnetic activity indices in a event; $B_0$, $V_{m}$ maximum IMF intensity and solar wind speed; $V_{m}$, $B_0$ – parameter of the solar wind disturbance normalized to $V=400$ km/s and B=5 nT; $t(V_m)$, $t(B_0)$, $t(Axym)$, $t(\Delta m_{min})$ – time from the onset to maximum values of the SW velocity, IMF intensity, CR anisotropy and $\Delta m_{min}$; $R_0$ – see in the text; $t_{min}$ – time from the onset to the CR density minimum; $A_F/B_0$ – ratio between the FE magnitude and maximum of the IMF intensity.

It is evident that average value of $A_F$ in S-group practically twice more than in group NS (2.27±0.08 % and 1.12±0.01 %). $A_F$ distribution (figure 2) shows that the maximum of events of S-group is visible. FEs with $A_F<1$% for NS-group constitutes about half the events (1218), and for S-group only 88 (~1/6). If select the events with $A_F<2$% in NS-group there will be 2172 events (near 90% of all), and in S-group – 297 (about 55%). In figure 2 the big quantitative prevalence of the big effects in S-group is visible. FEs with $A_F>6$% in NS-group make ~1/400 part, and in S-group 1/12 part, i.e., the large events belong, basically, S-group. By more detailed consideration it appears that all big FEs, are in full or partly related to CMEs.

<table>
<thead>
<tr>
<th>characteristic</th>
<th>S-group (SSC)</th>
<th>NS-group(no SSC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_F$, %</td>
<td>2.56±0.10(536)</td>
<td>1.13±0.02(2432)</td>
</tr>
<tr>
<td>$A_{ym}$, %</td>
<td>1.73±0.04(536)</td>
<td>1.22±0.01(2432)</td>
</tr>
<tr>
<td>$\Delta m_{min}$, %</td>
<td>-0.61±0.02(536)</td>
<td>-0.32±0.00(2432)</td>
</tr>
<tr>
<td>$A_{ym}$, nT</td>
<td>24.7±0.65(536)</td>
<td>36.09±0.55(2432)</td>
</tr>
<tr>
<td>$D_{min}$, nT</td>
<td>16.69±0.39(361)</td>
<td>10.81±0.09(1748)</td>
</tr>
<tr>
<td>$V_m$, km/s</td>
<td>569.9±6.3(354)</td>
<td>523.4±2.8(1725)</td>
</tr>
<tr>
<td>$B_0$, GV</td>
<td>9.41±0.17(324)</td>
<td>2.90±0.03(1618)</td>
</tr>
<tr>
<td>t($V_m$), hour</td>
<td>24.30±1.10(354)</td>
<td>25.88±0.55(1725)</td>
</tr>
<tr>
<td>t($B_0$), hour</td>
<td>10.33±0.71(361)</td>
<td>17.92±0.46(1748)</td>
</tr>
<tr>
<td>t($A_{ym}$), hour</td>
<td>18.87±0.84(536)</td>
<td>25.46±0.48(2432)</td>
</tr>
<tr>
<td>$R_0$, GV</td>
<td>39.35±3.48(189)</td>
<td>9.91±0.60(1211)</td>
</tr>
<tr>
<td>$t_{min}$, hour</td>
<td>20.86±0.71(536)</td>
<td>22.48±0.50(2264)</td>
</tr>
<tr>
<td>t($\Delta m_{min}$), hour</td>
<td>11.95±0.59(536)</td>
<td>18.79±0.39(2264)</td>
</tr>
<tr>
<td>$A_F/B_0$, %/nT</td>
<td>0.159±0.007(344)</td>
<td>0.109±0.001(1634)</td>
</tr>
</tbody>
</table>

Table 1. FE characteristics for two group.

If compare parameters of corresponding interplanetary disturbances $B_0$, $V_m$, $B_0$, $R_0$ all of them are bigger in S-group. The greatest distinctions turn out for $R_0$ – estimations of the maximum rigidity of particles which are capable to be reflected by magnetic field in the given interplanetary disturbance [2,10]. We have calculated $R_0$ for each event where SW measurements were complete enough, as follows: $R_0 = \sum_{i=1}^{n} (B_i - B_0)V_i$, where B and V – the IMF intensity and SW velocity, $B_0=7$ nT was chosen, and summation is conducted on hours from the FE onset ($t_0$) till a minimum of CR density. Mean values $R_0$ for two groups differ approximately in 4 times (39.4±3.5 (S) and 9.9±0.6 GV (NS)). We see that more strong interplanetary disturbances of group S create the bigger FE and higher geomagnetic activity. Average A$p$ indexes for S and NS groups are equal 72 and 34 (that...
We compare key parameters, characterizing the solar wind disturbance, maxima of IMF intensity \( B_m \) and of the SW speed \( V_m \) for each of the selected events (figure 3). From the general reasons it is clearly that they should correlate. The greater speed of CME or HSS, the more it compresses an interplanetary magnetic field. On the other hand, efficiency of interaction of SW stream with environment is essentially influenced by speed of a background solar wind, heliospheric current sheet, earlier created interplanetary disturbances etc. It is important that in many ejections (ICME) the maximum of the IMF intensity is often observed in a magnetic cloud [11] without direct relation to SW speed. It should not be surprised that correlation between \( V_m \) and \( B_m \) for S and NS groups exists, but correlation factors aren’t great (0.46 and 0.32).

From figure 3 it is visible that interplanetary disturbances of group S are stronger. The weakest (i.e. the slowest and with the weakest IMF) disturbances concern NS-group, and the strongest (fast and with great values of \( B_m \)), on the contrary, to S-group. At identical speeds the values of an interplanetary magnetic field may strongly differ, and regression line for S-group passes above those for NS-group. It means that in group S at the same speeds there are bigger interplanetary disturbances, than in group without shocks. Thereby, conditions for stronger modulation of galactic CR are created. The regression lines for these groups differ not only by a location but by the slope as well. Estimations of parameters of regressions \( B_m = a + b \times V_m \) give \( b_S = 0.027 \pm 0.003 \) for the S-group and \( b_{NS} = 0.011 \pm 0.001 \) for NS-group. It is well seen that coefficients have large enough difference. At increase of the maximum speed at 100 km/s the maximum intensity of IMF, on the average, increases on 2.7 nT in S-group and \( 1.1 \) nT in NS-group. In favor of that interplanetary disturbances of two groups are arranged differently, tell also distinctions in times of maxima of the SW speed \( t(V_m) \) and IMF intensity \( t(B_m) \) (Table 1). SS-group maxima come later (figure 4), especially for \( t(B_m) \). The maximum of speed lags behind maximum of the IMF on \( 8 \pm 1 \) hours for S-group, and on \( 280 \pm 20 \) hours for NS-group. We see that between groups exist not only quantitative, but also qualitative distinctions, hence, it, more likely, is two different distributions, than two parts of the same. Therefore it is possible to expect, that the mechanism of additional CR modulation will be various for groups that is confirmed by differences in the size of ratios \( A_F/B_m \) (0.159±0.007 and 0.109±0.001) which show that the same level of the IMF intensity leads to essentially greater modulation in S-group.

### Figure 4. Schematic presentation of the mean FD in groups S and NS corresponding to Table 1.

About features of CR modulation in various groups of events can tell relation of the FE magnitude to various parameters: as external (parameters of the interplanetary environment), and internal (characteristics of FE). One of such internal parameters is \( \Delta_{\text{min}} \) (figure 5), showing, on how many percent per hour is maximum decrease of the CR density in the given event.

Correlation coefficient \( \rho = -0.79 \) between \( \Delta_{\text{min}} \) and \( A_F \) in S-group. In the NS group a correlation is worse \( (\rho = -0.57) \), but still is sufficiently evident. This allows an estimation of maximum \( A_F \) on a descent phase of CR intensity, herewith the results will be different for two groups. For example, if \( \Delta_{\text{min}} \) is 2% then for event in S-group (in accordance to regression line in figure 5) \( A_F \) is expected to be \( \approx 7.3\% \), and in NS group \( \approx 6.1\% \). Difference in time evolution of effect in different groups is also noticeable (figure 4 and Table 1). Decreases in S-group evolve faster, minimum is deeper and reached earlier than in NS group. The times \( t(\Delta_{\text{min}}) \) differ even stronger than \( t_{\text{min}} \). Minimum of FD in S-group comes in average in \( 8.9\pm0.9 \) hours after \( t(\Delta_{\text{min}}) \), but in NS group difference of the times is essentially less – \( 3.7\pm0.7 \) hours. It is necessary to note also an important similarity of two groups: in both groups the greatest fall of density \( t(\Delta_{\text{min}}) \) is observed at once after a maximum of IMF intensity \( t(B_m) \).

Relation between \( A_F \) and components of CR anisotropy is also different for S and NS groups. Such a difference reveals also in the times of maximum values of anisotropy \( A_{\text{sym}} \) in two groups (Table 1, figure 4): in S group \( t(\Delta_{\text{min}}) = 18.9\pm0.8 \), but in NS group \( t(\Delta_{\text{min}}) = 25.5\pm0.5 \), maximum anisotropy is observed before minimum of FD in one group and in the other – after.

In figure 6 behavior of the FE amplitude \( A_F \) is presented versus parameter \( V_mB_m \). Significant distinguish is seen between two groups: the events within a group S have higher speed and IMF intensity. If \( V_mB_m > 8 \), then 35 events will be selected for S group (~1/15) and 14 events (~1/174) for NS group. At \( V_mB_m < 15 \) NS events are absent at all. Relation between \( A_F \) and \( V_mB_m \) are different.
for two groups (regression coefficient $b_s = 0.46 \pm 0.03$ in $S$ group, and $b_n = 0.21 \pm 0.01$ for $NS$ group). At the same interplanetary disturbance the events in $S$ group are followed by greater FE than events in $NS$ group. For example, if $V_mB_m = 10$ then mean $A_F$ in $S$ group will be $\approx 4.9\%$, and for events in $NS$ group $\approx 2.6\%$. Such a difference supposes that in various groups different sources of solar wind disturbances prevail. When instead of $V_mB_m$ another characteristic of the SW disturbances was taken, for example, $B_m$ or $R_B - CR$ modulation was also more effective in $S$ group as compared with $NS$ group.

![Figure 5. Relation between $A_F$ and $\Delta_{min}$](image)

![Figure 6. Dependence $A_F$ on the parameter $V_mB_m$ (characteristic of the solar wind disturbance)](image)

![Figure 7. $A_F$ versus Ap-index of geomagnetic activity](image)

It is argued that interplanetary disturbances not only have various structure but they modulate CR by different way. We may suggest different mechanisms of CR modulation in two groups, which associated with dominated role of CME (in $S$ group) or HSS from coronal holes (in group $NS$). Strictly saying, the results are obtained for special selections from which close by the time events were excluded. It seems, there was excluded more events caused by CME and this could change the results a little.

In figure 7 dependence of the FE magnitude on Ap-index of geomagnetic activity is shown. All the events were divided accordingly to a level of geomagnetic activity by the maximum Kp-index. One can see that large geomagnetic storms exist in both groups but at one geomagnetic activity a magnitude of FE in $S$ group is essentially bigger than in $NS$ group. It is evident that $S$ group predominates for all classes of big storms. Interplanetary disturbances in $NS$ group are effective enough for geomagnetic activity but they less effective in the CR modulation. Sometimes after gradual onset a great magnetic storm may evolve but very big FD in this case is less probable.

## 4 Main conclusions

The database on Forbush-effects and interplanetary disturbances is large enough and can be used for comparative statistical analysis of events of various types. Samples of events with sudden (S-) and gradual onset (NS-group) are essentially different. In $S$-group there were on the average more powerful events. Interplanetary disturbances of two groups differ also on structure. The interplanetary disturbances related to $S$-group, modulate cosmic rays more effectively and create larger FE as compared with the disturbances of $NS$-group having similar characteristics. To the same levels of geomagnetic activity in $NS$-group corresponds FEs of smaller size, than in $S$-group. The obtained results testify that in the selected groups different mechanisms of modulation of galactic cosmic rays prevail. Apparently, $S$-group events are mostly caused by CMEs while the considerable part of events of group $NS$ is connected with high-speed streams of plasma from coronal holes.

## 5 Acknowledgements

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## 6 References