On Cosmic Ray Decreases, Geomagnetic Storms, and CMEs

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Abstract. In this work we present preliminary results of our study of relationship between Forbush decreases (FD), geomagnetic storms and their connection to solar activity. FDs are reported to be connected with Halo Coronal Mass Ejection (H CME). A comprehensive catalogue based on combination of the FD catalogue [Eroshenko, 2011; 2013], data from NASA OMNIWEB and lists of CMEs and ICMEs allows us to make a statistical study. This is an updated and amended version of paper by Parnahaj et al. [2013].

Introduction

Low energy galactic cosmic rays (GCR) variations are detected with neutron monitor (NM, first design by J.A. Simpson during IGY). For a review of CR modulation see, e.g., Venkatesan and Badruddin [1990]. Sometimes a rapid decrease named Forbush decrease (FD, [Forbush, 1937]), characterized by a sharp decrease (few hours) and gradual recovery (days) is observed. It is connected with the interplanetary counterparts of a coronal mass ejection (CME) passing the Earth’s orbit. Along with the CMEs also the interplanetary shocks and stream interaction regions can cause FDs [e.g., Venkatesan et al., 1992]. This effect will be studied in the paper under preparation. FDs are often accompanied by geomagnetic storms (GS), but it is not “one to one” correspondence between the two phenomena. Complicated relationship between FD and GS is shown, e.g., in Kudela and Brenkus [2004] or Kane [2010]. Kane [2010] has investigated severe GS and FD during solar cycle 23 and their connection with interplanetary parameters. Using Dst index [definition in Sugiura, 1964], GS can be classified into three groups [Rockenbach et al., 2011]. Relations between CR FDs and Dst depressions are studied since the paper of Forbush [1937]. Although there is observed correlation between sudden Dst depressions (GS, geomagnetic storms) and FDs (as seen also from Figure 3b), the correlation is not very high and there are FDs without GS and also GS without FDs. Because of increase of data on CR, on interplanetary plasma and magnetic field as well as on geomagnetic activity indices, it is of some interest to continue to study these relations during various conditions in interplanetary space. One of the reasons of such studies (both statistical as well as case ones) in relation to space weather is e.g. discrimination between the effects on ionosphere (change of CR particle flux, change of geomagnetic field alone). Study of precursors in CR flux before FDs [known for long time, e.g. in book Dorman, 1974] is still actual: recently, e.g., Papailiou et al. [2013] have shown that before geomagnetic storms and FDs caused by CMEs with the source in western heliolongitudes, the precursors in CR anisotropy was reported to be very often.

CMEs, especially halo CMEs seem to be a cause of large FDs. CMEs, gigantic clouds of plasma with high magnetic field ejected from the Sun carrying away a lot of solar material into the heliosphere. A typical CME may have distinctive features as a cavity of low electron density, a dense core, and a bright leading edge. Solar flares, generally accompanied by CMEs, are produced in the solar active regions that have a complicated magnetic configuration with closed magnetic field lines. Description of CMEs and their connection to CR intensity variations can be found in various papers [e.g., Gopalswamy, 2009; Lara et al., 2005; Cane, 2000]. Lara et al. [2005] studied the evolution of CMEs observed by LASCO during the ascending, maximum, and descending phases of solar cycle 23 and their relation with the modulation of galactic cosmic ray intensity observed by Climax NM. Babu et al. [2013] attempted to identify if FDs are caused by CMEs from the Sun that are directed towards the Earth, or by their associated shocks. Their observation leads to the result that the primary contributors to FDs observed in high rigidity CRs are the Earth-directed CMEs. Mavromichalaki and Paouris [2012] studied the GCR modulation in relation to indices of solar activity and heliospheric parameters during the solar cycle 23 and the ascending phase of cycle 24 using CME-index.

Interplanetary coronal mass ejection (ICME) is interplanetary counterpart of CME. Common
signatures for ICME can be found in Richardson et al. [2006] and their relationship to the FDs have been described in several publications. Richardson and Cane [2011] examined > 300 ICMEs and their associated shocks passing the Earth in 1995–2009, FDs occurred during the passage of ICMEs in 80% of cases. Kilpua et al. [2011] examined the properties of ICMEs and found that compared to the ICMEs observed during the minimum following solar cycle 22, the maximum magnetic fields of the ICMEs during the minimum following solar cycle 23 were \( \approx 30\% \) lower and their radial widths were \( \approx 15\% \) lower. Blanco et al. [2013] analyzed the role of 59 shock-driving ICMEs on FDs detected by the Oulu NM and found only 25% of them were associated to the FDs > 3%. Mustajab and Badruddin [2013] studied the relative geoeffectiveness of various structures and features associated with ICMEs in producing geomagnetic disturbances.

Some wide CMEs forming a halo around the Sun with their apparent width of 360° are called Halo CMEs. Partial halo CMEs have width between 120° and 360° [Gopalswamy, 2009]. If ICME contains southward magnetic field (IMF) component, a crucial condition for geomagnetic storms [e.g., Tsurutani et al., 1988] is fulfilled. Important for solar wind-magnetosphere interaction are also magnetic clouds (MCs). When an ICME hits the Earth’s magnetosphere, most of the incoming material is deflected away by magnetic field. If the shock wave is very strong, it can compress the magnetosphere and unleash a geomagnetic storm. Verma et al. [2009] reported that for halo CMEs associated with X-ray solar flares and related to interplanetary shocks, MCs are responsible for large FDs and GS. Gopalswamy [2009] showed that if partial halo CMEs is considered, the geoeffectiveness is lower. Kane [2010] concluded that all interplanetary disturbances having shocks and directed towards the earth are geoeffective.

Here we present preliminary results of the statistical study on the relation between the amplitude of FDs and characteristics of solar, interplanetary and geomagnetic activity using the data on FDs, CMEs and ICMEs, especially for period 1996–2006.

Data

We prepared a catalogue by combining the three different catalogues. We have selected 392 halo CMEs from LASCO CME list (http://cdaw.gsfc.nasa.gov/CME_list/). Data of near-Earth ICME are taken from ACE list (http://www.ssg.sr.unh.edu/mag/ace/ACElists/ICMEmap.html) [Richardson and Cane, 2007]. This list contains information about time of disturbance typically related to the arrival of a shock or ICME leading edge at Earth, mean ICME speed and magnetic field, evidence of Bidirectional suprathermal Electron (BDE) and Bidirectional energetic Ion Flows (BIF), MC and CME has been reported in association with the ICME. Some information about interplanetary shocks were taken from (www.ssg.sr.unh.edu/mag/ACElists/obs_list.html) and (http://umtof.umd.edu/pm/figs.html). Comparing both catalogues we found that out of 392 halo CMEs, only 96 of them were associated with the ICMEs and shock that caused the disturbance at Earth. Third catalogue includes information about FDs, geomagnetic storms, solar wind maximum speed and interplanetary magnetic field (IMF) we took from [Eroshenko, 2013; Belov, 2009]. It consists of 6594 events of FDs from Moscow NM in 1957–2012 along with data on Dst, IMF and solar wind. Out of them 1115 FDs have amplitude > 2%. We used 250 FDs for our studies from 1996 to 2006. Comparing with previous two catalogues we found only 25.2% (63 of 250 FDs) associated with halo CMEs, the other 74.8% were identified as “non Halo” CME. By combining the three mentioned catalogues we constructed a combined one for statistical studies.

Case study

Figure 1 shows examples of two different events, both related to the halo CME. While the CR decrease in right panel (Mar 6–21, 2012) is accompanied by Dst depression, the CR event in left panel (Apr 11–21, 2013) not. Hourly averages time resolution data from the Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) and from the magnetic field experiment (MAG) on board ACE spacecraft have been used. Dst data are taken from World Data Center for Geomagnetism, Kyoto (Japan). CR intensity data are taken from three European NMs with different geomagnetic cut-off rigidity (Oulu, Moscow and Lomnicky stit), normalized for the first day. In both cases, the time of arrival of CME is accompanied by a sharp increase in density and speed of the solar wind (right event shows long lasting recovery phase consist of several depressions corresponding to sharp solar wind
Figure 1. Examples of different relations between FD and geomagnetic activity. Each panel shows Bz (Bt) of IMF, solar wind density (n) and speed (v), Dst, and CR normalized to the day indicated.

speed and density increases, CR decreases and Dst depressions). Noticeable difference is in Bz component of interplanetary magnetic field (IMF) in case of these two panels. While on the left panel Bz > 0 (not associated Dst depression), on the right panel Bz < 0 accompanied by a strong Dst depression (classified as Intense storm).

Distribution of FDs (1996–2006)

Relations between CR decreases and Dst depression for 1996 –2006 were examined. Out of total number of 250 FDs, 15.6 % of FD was > 6 %, 6.8 % was > 8 % and 2.8 % was > 10 %. On the other side 1.6 % of 250 events was > 6 % and Dst was < –200 nT. In the studied period there were identified 77 MSt, 56 ISt, and 11 SSt associated to FDs. Table 1 shows the statistical results based on Eroshenko [2013] and Belov [2009]. We would say, that strong FDs are associated with strong geomagnetic storms and vice versa, but not always. In previous case study we had two strong FDs, but only one of them was associated with Dst depression. During solar minimum (1996–1997) we identified only 9 FDs (> 2 %) associated to 4 MSt and to 2 ISt. During maximum (1999 –2002) out of the total 146 FDs 37 were connected to MSt, 31 to ISt and 5 to SSt. Figure 2 displays the distribution of FDs and CMEs with proportion of halo events.

Table 1. Distribution of geomagnetic storms accompanying the FD above given threshold

<table>
<thead>
<tr>
<th></th>
<th>Events</th>
<th>6 % &lt; FD &lt; 8 %</th>
<th>8 % &lt; FD &lt; 10 %</th>
<th>10 % &lt; FD</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST (Dst &lt; –250 nT)</td>
<td>22</td>
<td>0.0 % (0)</td>
<td>20.0 % (2)</td>
<td>57.1 % (4)</td>
</tr>
<tr>
<td>ISt (–250 &lt; Dst &lt; –100)</td>
<td>40.9 % (9)</td>
<td>70.0 % (7)</td>
<td>42.9 % (3)</td>
<td></td>
</tr>
<tr>
<td>MSt (–100 &lt; Dst &lt; –50)</td>
<td>36.4 % (8)</td>
<td>0.0 % (0)</td>
<td>0.0 % (0)</td>
<td></td>
</tr>
<tr>
<td>No Storms</td>
<td>22.7 % (5)</td>
<td>10.0 % (1)</td>
<td>0.0 % (0)</td>
<td></td>
</tr>
</tbody>
</table>

The catalogue [Eroshenko, 2013; Belov, 2009] consists of 6594 events of FDs covering period since 1957 until 2012 with information about Dst, IMF and solar wind speed. It allows to make high statistics. Figure 3 shows the scatter plots of the relations of FDs to Dst (left panel) and to IMF and solar wind speed (right panels). Due to non-availability of IMF and solar wind speed during some of the FDs, the number of events is different in different panels. Linear correlation coefficient between FD and Dst is $r = -0.51 \pm 0.018$. Significance was tested using the t test (here we used for simplicity the calculator at http://www.vassarstats.net/rsig.html). For scatter plot in Figure 3 left the estimate $-0.51$ is for 6128 points, thus the probability ($p$) that $r$ for the whole population is zero, is less than 0.001. For limited
extent of the paper we did not put there the details. Right panels show, that FD and Dst have better correlations with IMF than with solar wind speed; however, the correlation has not significantly increased by using $B \cdot v^2$. Regressions lines are mainly biased by the small FD, regression for FDs in three groups like in Figure 2 right top panel is in progress, not included here.

Figure 4 shows scatter plots of FD amplitude versus Dst in minimum after separating all events (250 FDs) to halo CMEs (H, 63) and “non halo CMEs” (NH, 187). Slightly higher correlation coefficient between FD and Dst are found for H than NH events. It seems to be larger variance of the Dst for H than NH events, and NH events are more concentrated in a small interval of FD amplitude (between 2 % and 5 %). Assuming the same distribution as above, we have for (187, –0.276) $p = 0.00013$, for (63, –0.40) $p = 0.0012$. In the brackets here is (number of points, estimate of rho).

Figure 5 illustrates cumulative distribution and shows the similar difference. For H events FDs with amplitude $< 4 \%$ are found in 37 % of cases, and for NH in 82 % of cases. FDs with amplitude $< 6 \%$ are found in 58 % for H events while in 94 % for NH events, similar differences are at higher thresholds. By separating H and NH events, Table 2 summarizes linear correlation coefficients ($R$) between FD, Dst and solar wind speed ($V_{sw}$), IMF ($B$). Better correlations are for H than NH events. Values $p$ (one-tailed) as mark of significance of differences in $R$ for H and NH events and $z$ statistics values we obtained from http://www.vassarstats.net/rdiff.html.

**Conclusion**

Preliminary results of relationship between FD and Dst indicate a rather complicated character. Linear correlation coefficient between FD and Dst in the whole FD catalogue is $r = –0.51 \pm 0.018$. Although only 25.2 % of FDs were associated with halo CMEs, they show better correlations (better binding FD and Dst with $V_{sw}$ and $B$) than non halo events. Halo CMEs produce larger FDs than non halo ones (Figures 4 and 5). Further analysis based on splitting data according to shocks, bidirectional electron streaming events and MCs may help to resolve complicated relationship between FD and Dst.

The results of statistical study here have several limitations. One of them is more detailed selection of the FDs with small amplitude (which can be in some cases masked by other types of variability) and we do not include here the geomagnetic effects acting as changes of transmissivity for GCR during the FDs with small Dst depressions as recently reported by Alania et al. [2013]. This is a first step in statistical study between FDs and Dst depressions using large collection of FDs.
Figure 3. (a) Scatter plot FD amplitude vs Dst min. (b) Scatter plots of FD amplitude versus solar wind speed and magnitude of IMF. (c) The same plots for Dst.

Figure 4. Minimum Dst versus FD amplitude for halo and non-halo events. Number of points and estimate of linear correlation coefficient are indicated.
Table 2. Summary of correlation coefficients (R) between FD, Dst and IMF (B), solar wind speed (Vsw) for separated halo and non-halo events.

<table>
<thead>
<tr>
<th></th>
<th>R_H</th>
<th>N_H</th>
<th>R_NH</th>
<th>N_NH</th>
<th>Z</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>FD vs Dst</td>
<td>-0.40</td>
<td>63</td>
<td>-0.28</td>
<td>187</td>
<td>-0.96</td>
<td>0.1685</td>
</tr>
<tr>
<td>FD vs Vsw</td>
<td>0.63</td>
<td>61</td>
<td>0.39</td>
<td>183</td>
<td>2.16</td>
<td>0.0154</td>
</tr>
<tr>
<td>FD vs B</td>
<td>0.49</td>
<td>62</td>
<td>0.33</td>
<td>183</td>
<td>1.34</td>
<td>0.0901</td>
</tr>
<tr>
<td>Dst vs Vsw</td>
<td>-0.53</td>
<td>61</td>
<td>-0.28</td>
<td>183</td>
<td>-1.99</td>
<td>0.0233</td>
</tr>
<tr>
<td>Dst vs B</td>
<td>-0.79</td>
<td>62</td>
<td>-0.62</td>
<td>183</td>
<td>-2.31</td>
<td>0.0104</td>
</tr>
</tbody>
</table>

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