ICMEs as Sources of Non-recurrent Forbush Decreases

Stephen Kahler* and George Simnett†

*Air Force Research Laboratory, Space Vehicles Directorate, 29 Randolph Rd, Hanscom AFB, MA 01731, USA
†School of Physics and Astronomy, University of Birmingham, B15 2TT, UK

Abstract. Forbush decreases (FDs) in neutron monitor (NM) counting rates are caused by enhanced magnetic fields in interplanetary shocks and solar ejecta that shield the Earth from galactic cosmic rays (GCRs). The solar origins of those ejecta can be observed as coronal mass ejections (CMEs) in coronagraphs and in heliospheric imagers such as the Solar Mass Ejection Imager (SMEI), launched into Earth orbit in January 2003. In our previous ICRC work [11] all FDs of > 2% observed with the Oulu NM through May 2005 were compared with SMEI observations to search for the white light signatures of interplanetary CMEs (ICMEs) responsible for the FDs. We now expand the FD-ICME study through the end of 2008 using updated SMEI and LASCO CME catalogs and a higher > 3% FD threshold to test our earlier result and characterize the ICMEs associated with FDs. We found an excellent association of SMEI CMEs with those FDs and for each of the associated SMEI CMEs a good associated SOHO/LASCO CME candidate was also found. The SMEI heliospheric observations provide information on the approximate spatial locations and trajectories of large ICMEs that may result in FDs and hence can be useful as a space weather tool.

Keywords: Forbush Decreases, Interplanetary CMEs, Galactic Cosmic Rays

I. INTRODUCTION

SMEI is an instrument designed to detect and forecast the arrival of interplanetary coronal mass ejections (ICMEs) and other heliospheric structures which are moving towards the Earth [24]. The instrument contains three CCD cameras, each with a field of view of 60° × 3°, which are mounted onto the spacecraft such that they scan most of the sky every 102-min orbit. To exclude light from the solar disk, a baffle system allows sky viewing only to within about 20° of Sun center. The sunward pointing system is offset ∼ 8.7° south of the ecliptic plane. The detectors are sensitive over the optical waveband, and the sensitivity is adequate to detect changes in sky brightness equivalent to a tenth magnitude star in one square degree of sky. To detect large ICMEs in the SMEI field of view, stellar images and the signal from the zodiacal dust cloud are subtracted from the sky images. The SMEI instrument and mission are described in [6] and [10]. SMEI was launched 6 January 2003 on the Coriolis spacecraft into a Sun-synchronous polar orbit. In the first 1.5 years of operation SMEI observed 139 ICMEs, at least 30 of which could be tracked to 1 AU and beyond and were associated with major geomagnetic storms [25] (Figure 1).

Forbush Decreases (FDs) are transient decreases in the counting rates of GCRs that last typically for about a week. There are two basic types [4] of FDs. The first consist of recurrent decreases, with gradual onsets and more symmetric profiles. These are often associated with corotating interaction regions in the solar wind [18], [20] originating from long-lived coronal holes. FDs of the second type are marked by sudden onsets, reaching maximum depression in about a day, often in two
stages [4], and followed by a gradual recovery [23]. In both cases it is understood that the decreases in GCR intensities result from large-scale (> 0.1 AU) increases in the interplanetary magnetic fields that modulate the scattering and convection of the GCRs [5], [26], [2]. Note that the gyroradius of a 10-GeV proton in a typical solar wind field of 10 nanoteslas is 0.02 AU. GCR fluxes at 1 AU have generally been well anti-correlated with the occurrence rates of CMEs observed at the Sun [17] or at 1 AU [5]. In several specific cases [3], [15], [16] the GCR variations have been used to model the structures of ICME magnetic flux ropes.

Geomagnetic storms are also associated with ICMEs and have been the topic of many investigations, generally correlating ICME properties with the geomagnetic Dst index [27], [14], [29], [13], [21]. It would be useful to be able to forecast FDs, as we learn to use the white-light coronagraph CME and SMEI ICME observations to forecast geomagnetic storms [9], [25]. In principle, prediction of FDs should be somewhat simpler than prediction of geomagnetic storms since the former depend primarily on the magnitude of the interplanetary magnetic field enhancement while the latter depend on both the magnitude and direction of the field disturbance [19], [30]. Since we can’t remotely observe the approaching interplanetary magnetic field features that lead to FDs, we want to determine how the white light observations of ICMEs may be useful for forecasting FDs. ICMEs are characterized by enhanced magnetic fields and often preceded by turbulent fields, which may cause FDs by deflections and scattering, respectively. However, enhanced pressures in ICMEs may cause super-radial expansions [7] that decrease their ambient densities and thus cause many ICMEs to become undetectable in the SMEI observations of the inner heliosphere.

In our earlier work [11] we selected FDs of >2% observed with the Oulu neutron monitor to compare with SMEI ICMEs to determine how well the SMEI observed those ICMEs that resulted in the FDs. We found SMEI ICME candidates for all 14 FDs for which SMEI observations were available and LASCO CME associations [28] for each ICME. At that time SMEI observations were complete only through late 2004. We now have SMEI observations through the end of 2008, an additional 4 years, so we can do a more comprehensive survey through the end of solar cycle 23 to explore how SMEI observations of ICMEs can be useful in predicting FDs at 1 AU.

II. DATA ANALYSIS

We used neutron monitor records from the Oulu, Finland, Cosmic Ray Station to search for FDs over the period March 2003 through the end of 2008. That station is located at a high geographic latitude of 65° and has a low cutoff rigidity of 0.78 GV. In our previous work [11] we selected as FDs all >2% decreases in counting rates for which the maximum decrease occurred within 3 days of the onset. Here we have changed the decrease threshold to >3%, which omits only two events from our earlier work. Figure 2 shows the Oulu Neutron Monitor counting rate profile for the two FDs on 22 and 26 July 2004 of Table 1. From [11].

![Figure 2: The Oulu neutron monitor counting rate data showing the two non-recurrent FDs of 22 and 26 July 2004 of Table 1. From [11].](image)

<table>
<thead>
<tr>
<th>Date</th>
<th>Onset Date</th>
<th>Estimated Duration</th>
<th>Dst Index</th>
<th>IMF Intensities</th>
<th>GCR Intensities</th>
<th>CME Angular Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 July</td>
<td>11 August</td>
<td>~12 hours</td>
<td>-100</td>
<td>~20 nT</td>
<td>4% decrease</td>
<td>~200 km/s</td>
</tr>
<tr>
<td>26 July</td>
<td>13 August</td>
<td>~12 hours</td>
<td>-100</td>
<td>~20 nT</td>
<td>4% decrease</td>
<td>~200 km/s</td>
</tr>
</tbody>
</table>

Table I gives the onset dates and our estimated durations and decreases of all the non-recurrent Oulu >3% FDs through the end of 2008, followed by their estimated onset times at Earth based on times of associated increases in the IMF intensities (in italics) or, where available, their storm sudden commencements (SSCs). For each FD we list in columns 5 and 6 the date and time of first observation of a candidate associated ICME observed in SMEI. The seventh column gives ΔT, the time in hours by which the first SMEI observation of the ICME preceded the FD onset. Those are followed by the ICME azimuth angles measured in degrees counterclockwise (CCW) from solar north, and...
approximate angular speeds in the sky plane in degrees per hour measured on plots as shown in Figures 1 and 3. For SMEI ICMEs through July 2004 we took the data from Table I of [11]. Data for more recent SMEI ICMEs were taken from an updated list maintained at the Air Force Research Laboratory by D. Webb. The LASCO dates and times of first CME observations, azimuth angles measured CCW from solar north, and leading edge speeds of candidate associated CMEs are taken from the LASCO CME Catalog [28]. There were typically many LASCO CMEs over the ~2-day periods that we searched for each FD, but those we selected clearly stood out as exceptional in their widths and speeds. Figures 1 and 3 illustrate the large angular gap between the LASCO and SMEI fields of view that make the associations challenging. The last two columns give the approximate peak intensities of the interplanetary magnetic field $B$ in nanotesla and particle density $n$ accompanying each FD and were taken from level 2 data of the MAG and SWEPAM experiments on the ACE spacecraft at the L1 point.

SMEI observations were available for 26 of the 29 FDs in Table I. In only one case, on 14 June 2005, did we not find a reasonable candidate ICME in the SMEI observations. We note that we are using ICMEs identified in the SMEI observations prior to and independently of our identifications of the FDs. Besides the excellent FD-ICME associations, we also ask about the lead or warning times $\Delta T$ (column 7) that the SMEI data can provide. Those times range from 0 to 44 hours, with a median value of 17 hours. The largest $\Delta T$ of 44 hours is associated with the 24 August 2005 FD and is 11 hours longer than the second largest $\Delta T$ of Table I. We regard this ICME association as the weakest or least likely in the Table. The SMEI ICME list of D. Webb describes the 22 August ICME as a very faint arc, notes that there is interference from glare, and questions the reality of the feature as an ICME. In searching for an associated LASCO CME, we found an exceptionally fast (2378 km/s) halo CME observed on 22 August at 1730 UT, which would seem the most likely CME source of the 24 August FD about 1.5 days later. That LASCO CME occurred after the initial observation of our listed SMEI candidate, so we associated with the SMEI candidate the preceding fast (1194 km/s) halo CME observed in LASCO at 0131 UT on 22 August. The unusually long lead time of 44 hours and the presence of a more likely and later halo CME argue against our association, so a better summary here is that we find 24 good SMEI associations with 26 FDs. Of
the two non-associations, the 14 June 2005 FD was only 3% and was not accompanied by particularly enhanced magnetic fields or densities at ACE. On the other hand, the 24 August 2005 FD was a 6% decrease and was accompanied by very high magnetic fields and densities. We should also consider the possibility that a sufficiently large ICME may miss the Earth but still modulate GCRs when the Earth lies in its shadow.

The ICME speeds range over about a factor of 3 (0.7° to 3.3°/hr), but this might be expected from model calculations of ICME angular speeds based on the Point P and Fixed-φ methods [12], assuming various solar source locations. The median lead time of 17 hours for first identification of ICMEs with potential impact for FDs should apply as well for geomagnetic storms.

### III. Conclusions

The good association of 24 of the 26 >3% FDs with ICMEs observed in SMEI shows that SMEI observations can be a useful forecast tool for FDs. The associations found here appear to preclude the possibility we raised in the Introduction that super-radial expansions of the CMEs could diminish their enhanced densities and render them invisible in SMEI.

Several points require further study. First is the question of how well the density enhancements of the SMEI ICMEs correspond to the magnetic enhancements observed at Earth and how accurately their arrival times at Earth can be predicted. Transforming the observed elongation angles, angular speeds, and angular accelerations into linear distances, speeds and accelerations of the CMEs will require a much better understanding of the ICME geometry than we have at present. We do however, now have over 300 identified SMEI events through 2008 to use for such studies.

To validate further the ICME-FD association an inverse study to consider which or how many of the Earthbound SMEI ICMEs produce FDs remains to be done. There are not yet clear criteria for deciding whether a given ICME is expected to intersect Earth since elongation angles >90° can be expected even if the Earth does not intercept the ICME.

Finally, in this study we generally found a prominent preceding LASCO CME to associate with the subsequent Earthbound SMEI ICME and FD. A surprising recent result [8] of comparing the SMEI observations with the LASCO CMEs is that about a quarter of SMEI ICMEs have either unlikely or no CME counterparts in the LASCO observations. Such ICMEs could begin as strong solar magnetic eruptions containing negligible excess mass and unobservaable by LASCO but then sweep up enough material as they propagate through the interplanetary medium to become observable as ICMEs by SMEI. If they are intercepted by the Earth, FDs and geomagnetic storms could result.

### IV. Acknowledgements

We acknowledge use of the data from the Cosmic Ray Station of the University of Oulu provided on line at http://cosmicrays.oulu.fi/#database by the Sodankyla Geophysical Observatory. The LASCO CME data were taken from the CME catalog generated and maintained at the CDAW Data Center by NASA and The Catholic University of America in cooperation with the Naval Research Laboratory. SOHO is a project of international cooperation between ESA and NASA. SMEI is a collaborative project of the U.S. Air Force Research Laboratory, the University of Birmingham, U.K., NASA, the University of California at San Diego, and Boston College. Financial support has been provided by the Air Force, the University of Birmingham, and NASA. LASCO is a collaboration between the US Naval Research Laboratory, Washington, DC, the Max Planck Institute for Aeronomy, Lindau, the Laboratoire d’Astronomie Spatiale, Marseille, and the University of Birmingham.

### References