



The Presence of Turbulent and Ordered Local Structure within the ICME Shock-sheath and Its Contribution to Forbush Decrease

Zubair Shaikh^{1,2}, Anil Raghav^{2,3}, and Ankush Bhaskar¹

¹ Indian Institute of Geomagnetism (IIG), New Panvel, Navi Mumbai-410218, India

² University Department of Physics, University of Mumbai, Vidyanagari, Santacruz (E), Mumbai-400098, India; raghavani1984@gmail.com

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Abstract

The transient interplanetary disturbances evoke short-time cosmic-ray flux decrease, which is known as Forbush decrease. The traditional model and understanding of Forbush decrease suggest that the sub-structure of an interplanetary counterpart of coronal mass ejection (ICME) independently contributes to cosmic-ray flux decrease. These sub-structures, shock-sheath, and magnetic cloud (MC) manifest as classical two-step Forbush decrease. The recent work by Raghav et al. has shown multi-step decreases and recoveries within the shock-sheath. However, this cannot be explained by the ideal shock-sheath barrier model. Furthermore, they suggested that local structures within the ICME's sub-structure (MC and shock-sheath) could explain this deviation of the FD profile from the classical FD. Therefore, the present study attempts to investigate the cause of multi-step cosmic-ray flux decrease and respective recovery within the shock-sheath in detail. A 3D-hodogram method is utilized to obtain more details regarding the local structures within the shock-sheath. This method unambiguously suggests the formation of small-scale local structures within the ICME (shock-sheath and even in MC). Moreover, the method could differentiate the turbulent and ordered interplanetary magnetic field (IMF) regions within the sub-structures of ICME. The study explicitly suggests that the turbulent and ordered IMF regions within the shock-sheath do influence cosmic-ray variations differently.

Key words: Sun: coronal mass ejection (CME) – cosmic rays – magnetic fields – solar wind – ISM: structure – turbulence

1. Introduction

The interplanetary space is filled with cosmic-rays. The modulation of cosmic-rays eventuates from its interaction with the interplanetary magnetic field (IMF). The modulation becomes very prominent when the emission of a very large coherent magnetic structure known as the interplanetary coronal mass ejection (ICME) takes place at the surface of the Sun. The fast moving ICME in slow ambient solar wind provoke shock-sheath ahead of it. The propagation of this huge magnetic field structure (ICME magnetic cloud (MC)) with the shock-sheath in the heliosphere induces decrease in cosmic-ray flux. This could be demonstrated through the ground-based neutron monitors (NMs) around the globe, which continuously observe cosmic-ray flux (Lockwood 1971; Cane 2000). The sudden transient decrease in cosmic-ray flux caused by interplanetary disturbances is known as the Forbush decrease (Hess & Demmelmair 1937). The corotating interaction region (CIR) and ICME are main drivers of Forbush decrease. The CIR generates recurrent, symmetric, and weak Forbush decrease, whereas ICME induced Forbush decrease is non-recurrent, highly asymmetric, and strong in nature. Moreover, the magnetic field barrier and solar wind speed are considered to be the main drivers in ICME-associated Forbush decrease (Belov et al. 2001; Dumbovic et al. 2012; Bhaskar et al. 2016a, 2016b).

The past studies of Forbush decrease show either one-step or two-step cosmic-ray decrease profiles during ICME transit (Richardson et al. 1996; Cane 2000; Richardson & Cane 2010, 2011; Arunbabu et al. 2013). The two-step traditional model and observational studies of the Forbush

decrease profile indicate that the first step and second step are caused by different ICME sub-structures, i.e., shock-sheath and MC respectively (for example, Raghav et al. 2014). However, note that the one-step or two-step FD profile depends not only on the structure of the ICME but also on the geometric location of the observer (Richardson & Cane 2010). This can be explained as the one-step Forbush decrease profile if the observer passes only through the shock-sheath or MC (with weak shock-sheath) and two-step decrease if the observer passes through both of the regions.

Wibberenz et al. (1998) put forward the shock barrier model to understand shock-sheath contribution in Forbush decrease. This model considers the diffusion of cosmic-rays across the propagating diffusive barrier. This explains the depression of cosmic-ray flux is observed during shock-sheath transit across the Earth (Wibberenz et al. 1998). The one-step/gradual decrease in cosmic-ray flux is expected during complete transit of the shock-sheath region from this model. However, observations demonstrate one-step (corresponding to the small part of the shock-sheath) or multi-step decrease with respective recovery during its transit, which cannot be explained by this model.

Interestingly, Jordan et al. (2011) studied 233 ICME events, which should have produced two-step Forbush decreases, but only 13 two-step Forbush decrease events were observed. Therefore, they proposed to discard the classical two-step Forbush decrease model and suggested the possible contribution of local small-scale magnetic structure within ICME in Forbush decrease (Jordan et al. 2011). Moreover, Raghav et al. (2016), summarized general features of the Forbush decrease profile (see in Figure 1) and proposed the new classification scheme for Forbush decrease phenomena. Furthermore, they concluded that not only sub-structure (shock-sheath and MC), but also localized structure within the sub-structures have an

³ Principle author.

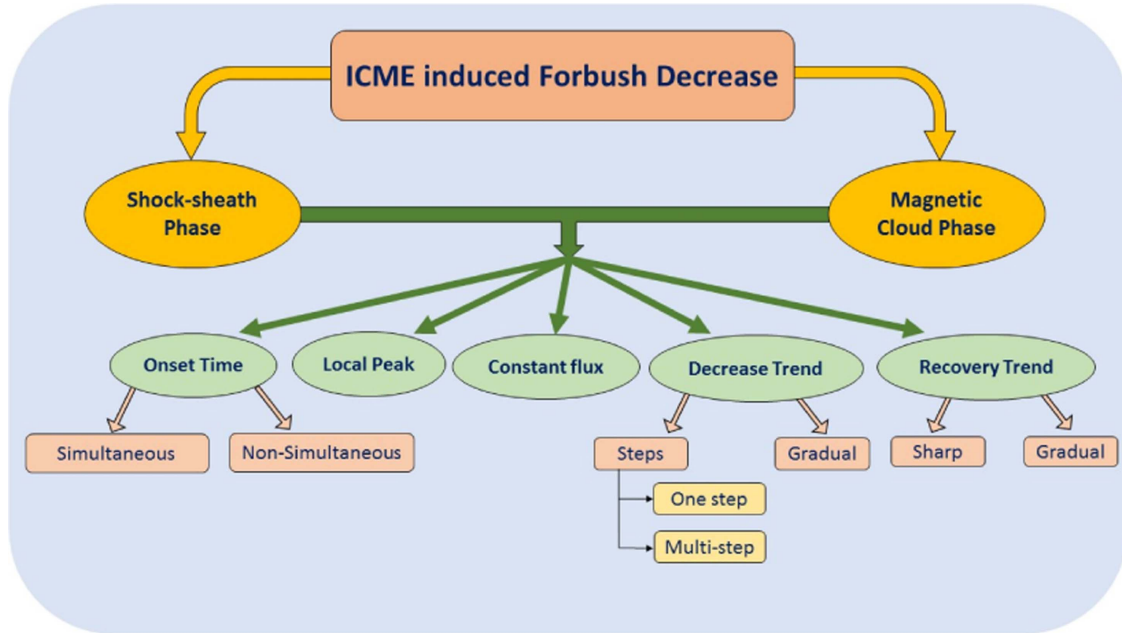


Figure 1. General features of the Forbush decrease profile during ICME transit given in Raghav et al. (2016).

effective role in the Forbush decrease profile (Raghav et al. 2016).

In light of the above discussion, it is important to study cosmic-ray variation during shock-sheath and MC transit independently and further evaluates the influence of local structures within sub-structures in detail. Thus, the main objective of the present study is to unravel the cause of the multi-step Forbush decrease as well as the recovery of cosmic-ray flux within the shock-sheath region.

2. Data and Methodology

To understand the cosmic-ray's response to the shock-sheath region, we have analyzed two ICME induced Forbush decrease events (amplitude $\geq 8\%$) that occurred on 2000 September 17 and 1998 September 24, respectively, from the catalog of the Neutron Monitor Database (NMDB at <http://www.nmdb.eu>). The neutron flux data from 51 NM observatories are available at nest2.nmdb.eu. However, for certain events, data from a few laboratories are missing. We have used neutron flux data (with 5 minute time resolution) retrievable at the above website for studied events. Each NM observatory has their local characteristics and baseline value of neutron flux. Therefore, we normalized the neutron flux intensity of each observatory. The normalized percentage variation (%) for each Neutron monitor observatory is defined as

$$N_{\text{norm}}(t) = \frac{N(t) - N_{\text{mean}}}{N_{\text{mean}}} \times 100, \quad (1)$$

where N_{mean} is averages of quiet day/days neutron flux of a specific observatory and $N(t)$ is neutron flux at time t of the same specific observatory. We have classified NM data into three broad energy windows, (1) low rigidity (0–2 GV), (2) Medium rigidity (2–4.5 GV), and (3) high rigidity (≥ 4.5 GV). The presented data for each energy band is the average normalized neutron flux of all observatory comes under given energy band.

To investigate the structure of the ICME (shock-sheath and MC topology) for studied events, we have used one-minute and five-minute time resolution interplanetary data from the OMNI

database cdaweb.gsfc.nasa.gov. The interplanetary parameters include the strength of IMF (B_{total}) along with the components B_x , B_y , B_z in (nT), solar wind speed (km s^{-1}), plasma temperature (K), proton density ($n \text{ cm}^{-3}$), and plasma beta.

The boundaries of the shock-sheath and corresponding ICME MC are adopted from the Richardson & Cane (2010). Generally, to identify shock-sheath boundaries, researchers have used (1) enhanced IMF with strong fluctuations, (2) enhanced solar wind speed, (3) high proton density, (4) high plasma temperature, and (5) high plasma beta. The Forbush decrease onset is determined by using visual inspection where neutron flux starts to decrease sharply.

To obtain a reliable estimate of physical quantities (for example, magnetic flux) of flux rope, it is necessary to find their correct orientation in the flux-rope frame. minimum variance analysis (MVA) facilitates the transformation of the single spacecraft frame data into the flux-rope frame and better visualize the flux-rope geometry. This technique has been extensively used to find the orientation of interplanetary structures (see, e.g., Sonnerup & Cahill 1967; Burlaga & Behannon 1982; Gulisano et al. 2007). Therefore, MVA is utilized in this study. However, note that this method gives quite well estimate of orientation of the flux-rope axis when its distance from the spacecraft trajectory is small compared to the radius of the flux rope (see, e.g., Klein & Burlaga 1982; Bothmer & Schwenn 1998; Gulisano et al. 2005).

After transforming the spacecraft data into the flux-rope frame using MVA, to visualize the geometry of the flux rope, we have used a hodogram representation. Generally, a 2D-hodogram method is used to visualize rotation/structures of IMF in space as well as in magnetospheric physics. The observation of the semi/circular pattern in one of the planes of B_x – B_y or B_x – B_z or B_y – B_z is a good indicator of the rotational structure present in the interplanetary space (Khabarova et al. 2015, 2016). However, temporal evolution or/and contribution of the third IMF component in magnetic structure cannot be studied using this 2D-hodogram method. Therefore, we have used 3D-hodogram method to effectively visualize the IMF configuration of different regions within the shock-sheath (Raghav & Zubair 2016). To

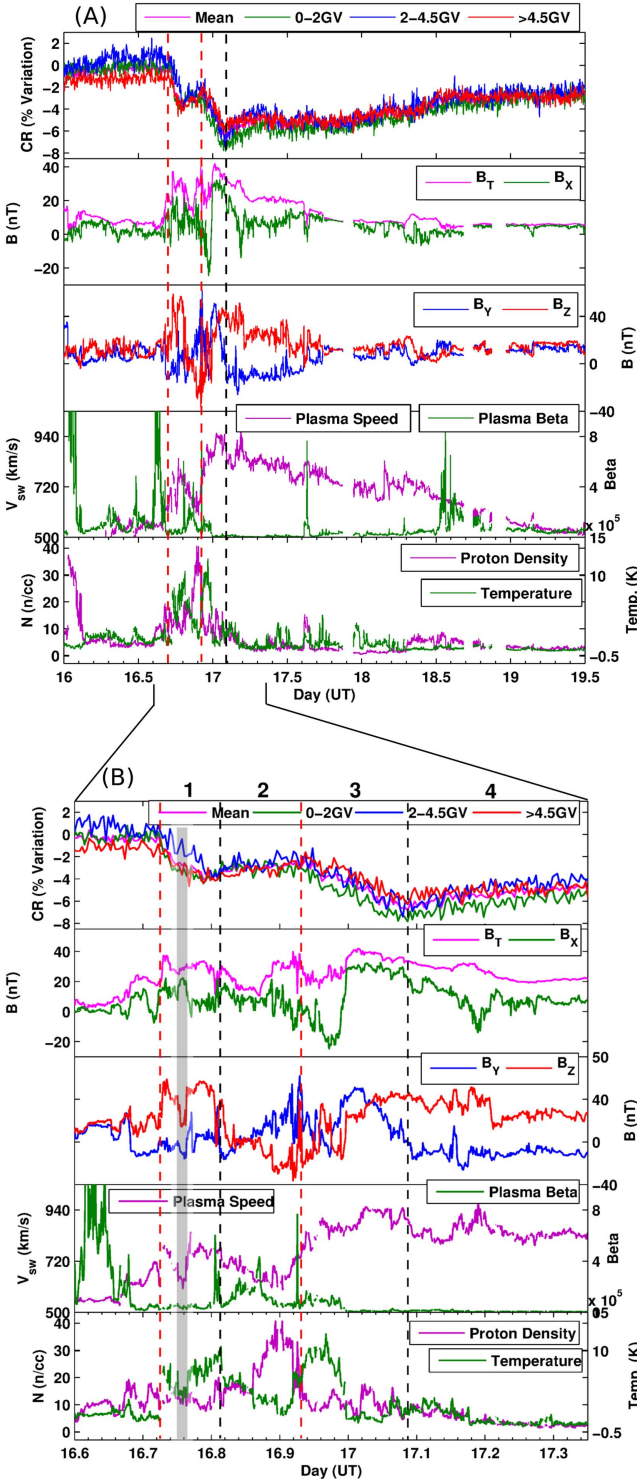


Figure 2. Forbush decrease event, which occurred on 2000 September 17. It has five panels, the topmost panel shows temporal variation of normalized neutron flux with their respective band of rigidities. The second and third panels show the interplanetary magnetic field (B_{Total} and its B_x -component) and (B_y and B_z -component) respectively. The fourth panel shows solar wind speed and plasma beta data respectively. The bottom panel shows proton density and plasma temperature variation. The shock-sheath boundaries are shown with red vertical dashed lines. The four different regions of the shock-sheath are separated by vertical dash lines.

make the hodogram, one-second time resolution IMF data from the ACE database <http://www.srl.caltech.edu/ACE/ASC/level2/> are utilized.

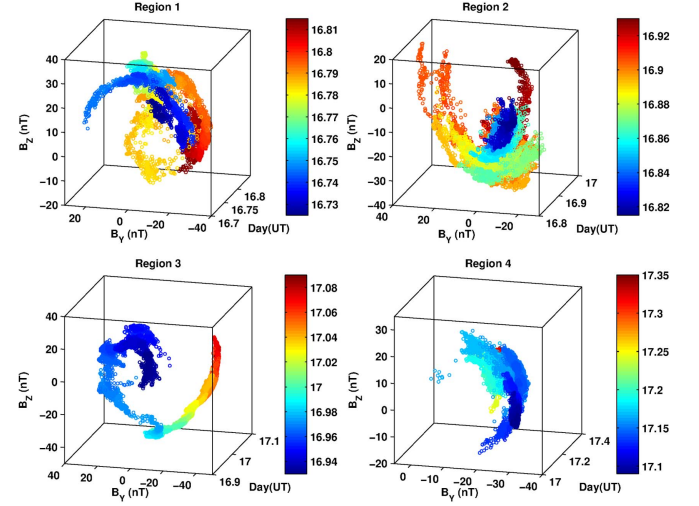


Figure 3. Four hodograms of the four shock-sheath regions as shown in Figure 5. Each hodogram represents the 3D projection of the magnetic field in the B_z - B_y plane, where the component B_x represents the in-out direction. The color bars show the temporal variation of the four shock-sheath regions. The top left and right hodograms are for regions 1 and 2, while the bottom left and right are for regions 3 and 4 as shown in Figure 2, respectively.

3. Observations and Interpretations

We have investigated two ICME shock-sheath regions to study the cause of cosmic-ray flux decrease and their recovery within shock-sheath. The shock-sheath region transit corresponding to the ICME event that occurred on 2000 September 17 (see Figure 2), exhibiting single step decrease following the recovery in cosmic-ray flux. Whereas, in 1998 September 24 (see Figure 4), the ICME shock-sheath transit demonstrated multi-step decreases and recoveries. For a detailed study, we have divided the shock-sheath region into sub-parts depending on the cosmic-ray flux variations. These sub-parts correspond to decreases and their respective recoveries in cosmic-ray flux within the shock-sheath. We have used the 3D-hodogram analysis technique to investigate the magnetic configuration of each sub-part of ICME shock-sheath.

3.1. 2000 September 17

The classical two-step, simultaneous Forbush decrease event that occurred on 2000 September 17 is shown in Figure 2. The sudden sharp enhancement in IMF, solar wind speed, and proton density indicate the arrival of ICME's shock at the Earth's bow shock (shown by the first vertical red dashed line). The cosmic-ray flux shows simultaneous gradual decrease accompanying with the onset of shock. The complete shock-sheath transit takes about ~ 5 hr (region between two vertical red dashed lines). However, the first step decrease is observed only about ~ 2.4 hr. During the rest of the shock-sheath crossing, the cosmic-ray flux shows slow gradual recovery. These observations manifest that only the front edge of the shock-sheath (mostly the shock front) contributes to cosmic-ray decrease, - whereas the remaining shock-sheath leads to recovery.

Similarly, after the onset of the MC, the cosmic-ray shows a gradual decrease for ~ 3.8 hr. Moreover, during the rest of the MC crossing, cosmic-ray flux recovery is observed. These observations suggest that the enhanced IMF strength contributes to the decrease during the onset of the MC. Whereas the gradual decrease in IMF strength gives rise to the recovery of cosmic-ray flux.

As noted earlier, based on cosmic-ray variations, we have divided the observed region into four local regions (sub-parts)

for this event. First and second local regions correspond to the decrease and recovery of cosmic-ray flux within the shock-sheath. Whereas, third and fourth local regions correspond to the decrease and recovery of cosmic-ray flux within the MC. The boundaries of local regions are indicated by vertical dashed lines, which are shown in Figure 2. Further 3D-hodograms have been constructed for better visualization of the IMF configuration during each local region crossing.

3.1.1. Region 1

During the crossing of local region 1, the total IMF shows enhancement in total field strength. All IMF components show fluctuations throughout the local region 1 except for a small interval of time in which B_y and B_z shows some rotation (see the gray shaded strip in Figure 2). This could be ascribed as the small magnetic island (Khabarova et al. 2015, 2016; Raghav & Zubair 2016) formation within local region 1. The effective visualizations of these observations could be seen in Figure 3. The left top hodogram clearly demonstrates that the initial (blue shade) and end part (red shade) of region 1 is highly fluctuating. Moreover, the only small time interval (shown as the sky-blue arc) are the evidence of magnetic island formation. In summary, we conclude that the high fluctuation in IMF is due to heating of shock-sheath plasma, i.e., turbulence present in local region 1 could be the cause of cosmic-ray decrease.

3.1.2. Region 2

The total IMF shows a gradual decrease followed by recovery with small fluctuations in local region 2 shown in Figure 2. Furthermore, the IMF components B_x , B_y , and B_z show gradual variation with some fluctuations. Besides this, the plasma temperature shows the decrease during region 2 transit. Moreover, the right top hodogram of Figure 3 clearly demonstrate the presence of various arc planes. This distinctly indicates the existence of the magnetic island within the local region 2. These observations evince that the magnetic structure could be causal to cosmic-ray flux recovery.

3.1.3. Region 3

In region 3, total IMF and its components show high fluctuations whereas, plasma temperature and solar wind speed depict enhancement for about ~ 1.7 hr. Further sudden increase/decrease in total IMF strength/plasma temperature is observed followed with a steady and slow decrease. The left bottom hodogram also demonstrates high fluctuations followed with a clear semicircle structure. These observations imply that the front edge of the MC is highly fluctuating, i.e., turbulent. However, the rest of region 3 indicates the unambiguous evidence of rotating magnetic structure, i.e., ICME flux rope. These observations reveal that the turbulent region and/or enhanced magnetic field strength region could be responsible for cosmic-ray flux decrease.

3.1.4. Region 4

The local region 4 is the part of the MC, which depicts a gradual decrease in total IMF with small fluctuations. The solar wind speed, plasma density, and temperature show steady variations. The 3D-hodogram demonstrates the various arc planes, which could be ascribed to rotational magnetic structure

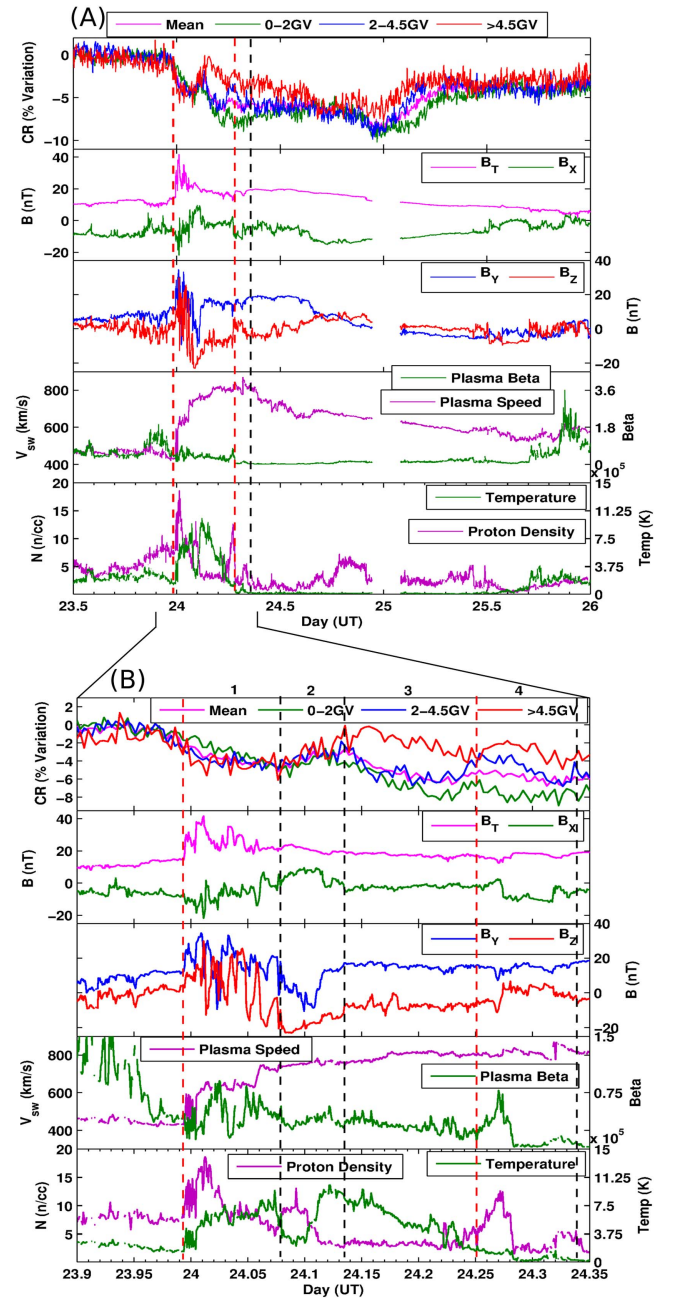


Figure 4. Forbush decrease event, which occurred on 1998 September 24. It has five panels, topmost panel shows the temporal variation of normalized neutron flux with their respective band of rigidities. The second and third panels show interplanetary magnetic field (B_{Total} and its B_X -component) and (B_Y and B_Z -component) respectively. The fourth panel shows solar wind speed and plasma beta data respectively. The bottom panel shows proton density and plasma temperature variation. The shock-sheath boundaries are shown with red vertical dashed lines. The four different regions of the shock-sheath are separated by vertical dashed lines.

i.e., the feature of MC. The cosmic-ray flux shows gradual and steady recovery, which indicates that the magnetically ordered structure contributes to cosmic-ray recovery.

3.2. 1998 September 24

The complex multi-step Forbush decrease event that occurred on 1998 September 24 is shown in Figure 4. It shows a two-step decrease in cosmic-ray flux with recovery within the shock-sheath region of ICME. The commencement of shock at

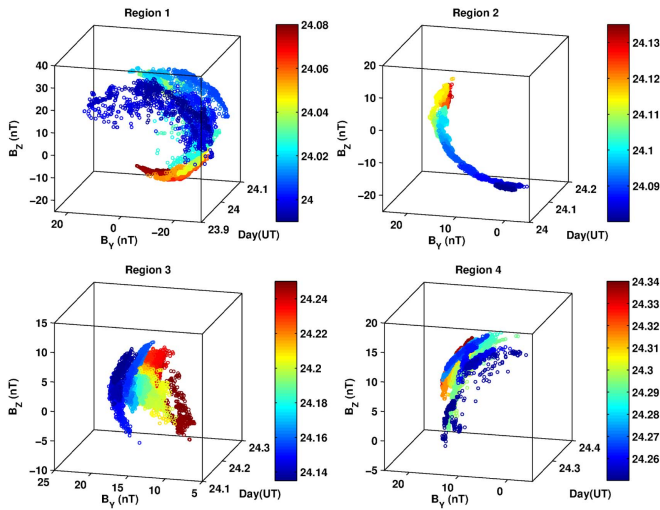


Figure 5. Four hodograms of the four shock-sheath regions as shown in Figure 4. Each hodogram represents the 3D projection of magnetic field in the B_z - B_y plane, where the component B_x represents the in-out direction. The color bars show the temporal variation of the four shock-sheath regions. The top left and right hodograms are for regions 1 and 2, while the bottom left and right are for regions 3 and 4 as shown in Figure 4, respectively.

the Earth’s bow shock (shown by the first vertical red dashed line) can be identified by the sudden sharp enhancement in IMF, solar wind speed, and proton density. The complete shock-sheath transit takes about 6.5 hr (region between the two vertical red dashed lines). The cosmic-ray flux starts decreasing well before the commencement of the shock. This might be due to the enhanced magnetic field before the commencement of the shock. The effective visualization of IMF structure within the shock-sheath region is demonstrated using a 3D-hodogram method. Figure 5 shows 3D-hodograms for all the sub-regions of Figure 4.

3.2.1. Region 1

The total IMF, solar wind speed, plasma temperature, and plasma density is significantly enhanced which is the signature of the compressed and heating nature in region 1. In region 1, strong stochastic fluctuations are observed in total IMF and its components. This can also be clearly seen in the top left hodogram in Figure 5. The hodogram illustrates that the front part of the region 1 is highly fluctuating (see blue shed). These observations suggest that the front edge of shock-sheath (shock front) is highly turbulent and significantly contributing to cosmic-ray flux decrease.

3.2.2. Region 2

During region 2 transit, the total IMF shows the steady slow decrease, while its components have smooth variations. A clear orientated structure (rotational) is observed, especially in B_y and B_z components of the IMF. The proton density and plasma temperature increase/decrease in this region, while the solar wind speed shows the slow gradual increase. All these observations can be interpreted as the formation of rotational structure within the shock-sheath region. The 3D-hodogram of the local region 2, is represented at the top right in Figure 5. We can clearly observe the rotational structure (semicircle) of the IMF in the y - z plane. This rotational structure/flux rope within

the local region 2 of the ICME shock-sheath seems responsible for the observed recovery of cosmic-ray flux.

3.2.3. Region 3

During the second step decrease (i.e., local region 3), a steady variation in the total IMF and its components B_x and B_y is observed, while the B_z shows small fluctuation. The plasma density, solar wind speed, plasma beta show steady variation, whereas the plasma temperature decreases gradually with small fluctuations. The circle arc planes with different arc length are observed in the bottom left 3D-hodogram. Note that the end part of region 2 has different arc length as compared to that of the initial part of region 3. However, the orientation of these arc planes is similar. This indicates that the rotational structures in local region 2 may be extended in local region 3. Interestingly, in local region 3, IMF is steady (non-decreasing strength) and has dawn to dusk orientation. This is clear evidence of flux-rope formation in the shock-sheath region. The steady and dawn to dusk oriented IMF in flux rope (observed in region 3) could be responsible for the slow and gradual decrease in cosmic-rays.

3.2.4. Region 4

Furthermore, in local region 4, the total IMF shows a small enhancement with steady variations; however, all of its components depict small fluctuations superposed over the steady variations. The solar wind speed and plasma temperature show steady variations, while the proton density and plasma beta show gradual enhancement followed by sudden decreases in its ambient value. The right bottom hodogram also depicts that the initial part of region 4 is fluctuating but the rest of it shows an oriented arc plane with different lengths. This region also has a similar rotational structure (flux rope) as those observed in regions 2 and 3, respectively, except at the initial part, i.e., at the transition region between shock-sheath and MC. Moreover, during this transit, we have observed an overall gradual decrease in cosmic-ray flux. The enhanced IMF field strength, along with the fluctuating IMF components could result in observed cosmic-ray flux decrease.

4. Discussion and Conclusions

The Forbush decrease phenomenon is interpreted on the basis of diffusion of cosmic-rays in the convecting IMF structure. This structure generally consists of two broad sub-structures, shock-sheath and flux rope (MC). The shock-sheath is mainly characterized by stochastic fluctuations of the magnetic field, whereas MC is identified as ordered magnetic structure (Cane 2000; Richardson & Cane 2011; Raghav et al. 2014). In general, the first step of Forbush decrease is generally ascribed to shock-sheath and the second one is due to MC (Wibberenz et al. 1998; Cane 2000; Arunbabu et al. 2013; Raghav et al. 2014). To be precise, the model by Wibberenz et al. (1998), which is based on the diffusion of cosmic-rays across the propagating diffusive barrier is widely used to explain cosmic-ray decrease during shock-sheath crossing. The one-step/gradual decrease in cosmic-ray flux has the direct implication of this model. However, this model does not clarify the origin of multi-step decrease and/or recovery during shock-sheath transit. Also, one-step, two-step, and multi-step complex events have been reported that suggest the contribution of local

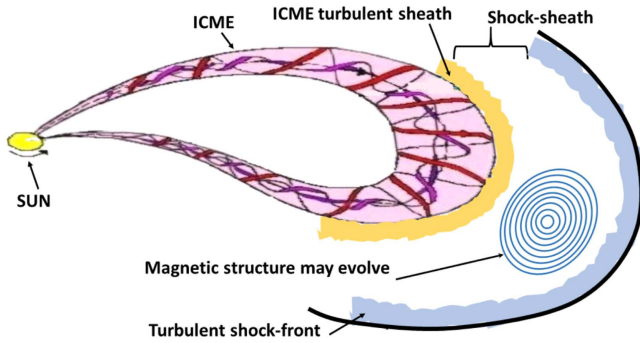


Figure 6. Schematic diagram of ICME evolution in interplanetary space.

structures within the sub-structures in the Forbush decrease profile (Jordan et al. 2011; Raghav et al. 2016). Moreover, which part of the shock-sheath or MC contributes to step/gradual decrease or/and in the recovery of cosmic-ray flux has remained an open problem. Here, we carry out a detailed investigation of the local magnetic structures within the shock-sheath region and their contribution to cosmic-ray decrease and/or recovery.

To address this issue, we have examined two large Forbush decrease events that occurred on 2000 September 17 and 1998 September 24. The first event shows the only one-step decrease with recovery and the second event illustrates two-step decrease with respective recoveries within the shock-sheath region. The 3D-hodogram method used in this work gave effective visualizations of magnetic configuration of the local structures formed within the shock-sheath region. Moreover, this method explicitly differentiates the turbulent and ordered IMF configuration.

This study clearly demonstrates that (1) the random fluctuations (i.e., turbulence) and strength of IMF contribute to the cosmic-ray decrease, (2) the ordered structure with almost constant magnetic field participate in cosmic-ray flux decrease, (3) the ordered structure with declining magnetic field strength participate in cosmic-ray flux recovery. The generally accepted view is that the shock front is turbulent due to plasma compression and heating, which contribute to cosmic-ray flux decrease. The presence of the ordered structure (magnetic island/flux rope) in the shock-sheath is intriguing and their origin is unclear at present. There exists another possibility, that the ordered structure (magnetic island/flux-rope evolves in the later part of the shock-sheath region as a consequence of plasma relaxation process Taylor (1986). The shock-sheath plasma is not perfectly conductive due to the presence of turbulence and therefore can reach Taylor state (low potential energy) by forming magnetic island-like structures within the shock-sheath. This newly evolved order structure within the shock-sheath can control the recovery of cosmic-ray flux.

Beside this, it is known that the density fluctuations in upstream plasma distort the shape of the shock front and also generate turbulent post-shock fluid Giacalone & Jokipii (2007). These shock waves can also generate reconnecting current sheets, large-scale low-frequency electromagnetic waves, and magnetic islands in the post-shock fluid (Karimabadi et al. 2014; Zank et al. 2015). Generally, magnetic islands originate from the dynamical processes of magnetic reconnection and turbulence (Greco et al. 2010; Markidis et al. 2013).

The role of magnetic islands may be important for particle acceleration in the solar wind via merging or contraction of magnetic islands. In summary, the shock can accelerate the particles through diffusive shock acceleration and magnetic-island-reconnection processes (Zank et al. 2015) and therefore, can affect fluxes of low energy particles in the interplanetary space.

Furthermore, MC reconnection with the shock-sheath may give rise to turbulent conditions resulting in a transition region between the sheath and MC. This process can be thought as follows. (1) Magnetic reconnection gives rise to the electric field. (2) The electric field accelerates charged particles. (3) Acceleration process increases the kinetic energy. Moreover, it should increase the plasma temperature. The signature of this is evident in Figure 2. (4) The net effect of these is the formation of the turbulent region just before the MC. The possible visualization using an artistic picture of ICME (shock-sheath and MC) and evolved magnetic structure within the shock-sheath is shown in Figure 6. In summary, observations illustrate that the transition regions, which are, in general, turbulent, and the front edge of the MC with enhanced IMF strength contribute to a cosmic-ray decrease. However, the rest of the MC contributes to the recovery of cosmic-ray flux due to the gradual decrease in magnetic field strength. However, it is possible that as ICME travels in interplanetary space, it drags away the already present magnetic island in the solar wind. The shock-sheath material of ICME is then contaminated by this structures and therefore, the magnetic island could appear as part of the ICME. These kinds of structures may also originate from ICME-ICME, ICME-CIR, and/or ICME-solar wind interactions.

We have estimated the width of the observed coherent structures in the shock-sheath and the gyro-radius of the studied GCR energy window. The width of the coherent structures in the shock-sheath is estimated by multiplying the duration and the average solar wind speed. The estimated width of the structure for the event that occurred on 2000 September 17 is $\sim 6.5 \times 10^6$ km, which can affect the cosmic-rays up to ~ 10 GV. Similarly, for the other event (1998 September 24), it is $\sim 3.6 \times 10^6$, which can modulate cosmic-rays up to ~ 6 GV.

In addition, the width of the turbulent structure in the shock-sheath is calculated by multiplying the duration and the average solar wind speed. The estimated thickness of the turbulent structure for the event that occurred on 2000 September 17 is $\sim 6 \times 10^6$ km. By accounting for this thickness and enhanced magnetic field, we have estimated the mean-free path of 1–10 GV cosmic-rays. We have assumed the $\sim 10\%$ turbulence level and maximum turbulence length scale ~ 1 au in the structure (Subramanian et al. 2009; Raghav et al. 2014). Interestingly, the estimated mean-free path of the cosmic-rays within the considered energy window is $\sim 10^6$ – 10^7 Km. The mean-free path is less or the same as the size of the turbulent region within the shock-sheath. Therefore, the turbulence level in this region is the most likely parameter, which decides the scattering of the cosmic-rays. These first-order estimates of gyro-radius, structure dimension, and mean-free path of cosmic-rays support the observations that the sub-structures within the shock-sheath affect the cosmic-rays.

In summary, the study explicitly shows that not only turbulent but also ordered IMF regions do exist in the shock-sheath region.

These ordered and turbulent regions affect cosmic-ray flux variations differently. These observations have significant importance for future studies of Forbush decreases and understanding their origin.

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