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Forbush Decrease: A New Perspective with Classification

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Abstract Sudden short-duration decreases in cosmic ray flux, known as Forbush decreases (FDs), are mainly caused by interplanetary disturbances. A generally accepted view is that the first step of an FD is caused by a shock sheath and the second step is due to the magnetic cloud (MC) of the interplanetary coronal mass ejection (ICME). This simplistic picture does not consider several physical aspects, such as whether the complete shock sheath or MC (or only part of these) contributes to the decrease or the effect of internal structure within the shock-sheath region or MC. We present an analysis of 16 large ($\geq 8\%$) FD events and the associated ICMEs, a majority of which show multiple steps in the FD profile. We propose a reclassification of FD events according to the number of steps observed in their respective profiles and according to the physical origin of these steps. This study determines that 13 out of 16 major events ($\sim 81\%$) can be explained completely or partially on the basis of the classic FD model. However, it cannot explain all the steps observed in these events. Our analysis clearly indicates that not only broad regions (shock sheath and MC), but also localized structures within the shock sheath and MC have a significant role in influencing

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the FD profile. The detailed analysis in the present work is expected to contribute toward a better understanding of the relationship between FD and ICME parameters.

Keywords Shock-sheath · Magnetic cloud (MC) · ICME · Cosmic ray · Forbush decrease · Local magnetic structures

1. Introduction

Sudden short-duration decreases in cosmic ray (CR) count observed on the surface of Earth by neutron monitors (NMs), followed by recovery times lasting from about a few hours to days and sometime even weeks, are known as Forbush decreases (FD) (Hess and Demmelmair, 1937). These decreases are typically caused by interplanetary counterparts of coronal mass ejections (ICMEs), which generally consist of a shock sheath and a magnetic cloud (MC) as a substructure (Barnden, 1973; Cane, 2000; Raghav *et al.*, 2014). The modulation of CR flux occurs through the interaction of MCs and the shock sheath with the convected interplanetary magnetic field. The study of these CR modulations could lead to insights in the structure of interplanetary disturbances (*e.g.* ICME shock or MC).

The ICME can be thought of as a closed low-density magnetic tongue-like structure that expands as it propagates through interplanetary space. If an ICME has a high speed relative to the background solar wind speed, it produces a shock-sheath region ahead of it. This magnetic field has an ordered and a turbulent component. The magnetic field of the CME is assumed to be frozen into the plasma. As the CME takes off, it is initially devoid of CR particles, but CRs diffuse into the ICME during its propagation. In spite of this diffusion, the interior of the ICME is still deficient in CRs as compared to its surroundings. When the ICME passes Earth, a decrease in intensity of CRs is therefore observed. This is how an FD takes place (Richardson and Cane, 2010, 2011; Vourlidas *et al.*, 2013). On the basis of the above model and understanding, FD events are classified into two categories: i) a one-step FD, and ii) a two-step FD. The observation of one-step or two-step FDs depends not only on the structure of the interplanetary disturbance, but also on the location of the observer. Because typically two regions are present (shock sheath and MC), the general nature of an FD is of two-step type. However, when the observer crosses only the shock sheath or only the MC, the FD manifests itself as a one-step decrease. One-step decreases are also observed when the ICME is less energetic (and hence without a significant shock sheath). This means that there are mainly three categories of FDs, which are caused by i) only the shock (one-step FD), ii) only the MC (one-step FD), or iii) a combination of shock and MC (two-step FD). Furthermore, an FD can be caused by a roughly equal contribution of the shock and MC (Richardson, Wibberenz, and Cane, 1996; Wibberenz *et al.*, 1998).

The role of an ICME in FD events has been studied intensively by many researchers around the globe *e.g.* Richardson, Wibberenz, and Cane (1996), Cane (2000), Richardson and Cane (2011), Belov *et al.* (2001, 2014), Belov (2008), Dumbović *et al.* (2011, 2012), Papaioannou *et al.* (2010), Bhaskar, Subramanian, and Vichare (2016). In spite of all these attempts to relate FD properties with measured parameters of ICMEs at 1 AU, there are significant gaps in our understanding of their underlying physical mechanisms. The reason could be due that the FD is a manifestation of large-scale interplanetary disturbances, whereas the spacecraft measurements are local and might not reflect the global property of the disturbance (Richardson and Cane, 2011). In addition, neutron monitors generally measure CR flux with an energy band of $\geq\sim 0.5$ GV to $\leq\sim 15$ GV. These energies correspond to a proton gyroradius of ~ 0.002 AU to ~ 0.13 AU, respectively, for an interplanetary magnetic field of ~ 5 nT. These gyroradii determine the minimum size that interplanetary structures must have to modulate CRs. The past studies indicate that interplanetary magnetic field and solar wind speed affect an FD significantly through cross-field diffusion and convection-diffusion (Richardson, Wibberenz, and Cane, 1996; Wibberenz *et al.*, 1998; Bhaskar *et al.*, 2016). The significant contribution of the turbulent sheath region of the ICME in determining the FD magnitude has been pointed out previously (Badruddin, 2002a,b; Raghav *et al.*, 2014; Candia and Roulet, 2004; Giacalone and Jokipii, 1999; Subramanian *et al.*, 2009). However, Jordan *et al.* (2011) proposed to reject the two-step FD model and emphasized the necessity of including the contribution of ignored small-scale interplanetary magnetic structure (Jordan *et al.*, 2011). In the light of this proposal, it becomes necessary to re-examine the 'traditional' understanding of the FD in detail.

As presented in the above discussion, it is well understood that the ICME is the primary driver in the non-recurrent FD. The literature suggest that the first step of a two-step FD is due to the shock sheath and the second step is due to the MC of the ICME. However, there are a few questions that are important to address, such as i) whether the complete ICME shock or the MC (or only some part of them) contribute to the CR decrease, and ii) whether any internal structure is associated with the ICME shock or the MC that is especially responsible for the decrease. Therefore we here carry out a detailed study of 16 strong FD events and associated ICMEs that occurred in the past two decades.

2. Data and Method

It is well known that the neutron fluxes measured by the world-wide network of neutron monitors (NMs) are good proxy of CRs, *e.g.* Bhaskar *et al.* (2017), Potgieter (2013), Vanhellemont, Fussen, and Bingen (2002). In this study, the neutron flux is therefore assumed to be directly proportional to the CR flux. The neutron flux data from 51 NM observatories are available at http://www.nmdb.eu. However, for certain events, data from a few neutron observatories are missing. On average, data from 30 – 35 observatories were available. The number of available observatories varies on an event-to-event basis. We used neutron count rate data (with 5-minute time resolution) that are retrievable at the above website for all studied events. Each NM observatory is located at a different altitude, latitude, and longitude and has a different vertical geomagnetic cut-off (*i.e.* rigidities), the detailed information is available online, at http://www.nmdb.eu. The 18 FD events were selected for investigation from 1998 to 2011 in the FD catalog available at the same database. The list of events used in this work is given in Table 1. Although an FD is a global phenomenon, individual observatories will have different baselines because of their respective instrumental characteristics and local parameters. To minimize these variations, we normalized the CR intensity of each observatory. The normalized percentage variation (%) for each NM observatory is defined as

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

where N_{mean} is the average of the previous day or days (quiet time) counts of a particular observatory, and $N(t)$ is the neutron count at time t of the same observatory. We used 5-minute time resolution interplanetary data taken from the OMNI database http://cdaweb.gsfc.nasa.gov and ACE database (4-minute averaged IMF data and 64-second averaged solar wind data) http://www.srl.caltech.edu/ACE/ASC/level2/ (ACE data

Table 1 List of analyzed Forbush decrease events classified on the basis of the number of steps observed in cosmic ray flux.

Event date	No. of steps in cosmic ray flux	
	SS	MC
1) One-step FD (caused by shock or MC phase)		
13 July 2000	1	0
18 Feb 2011	1	0
2) Two-step FD (caused by shock and MC phase)		
17 Sept 2000	1	1
11 Apr 2001	1	1
22 Jan 2004	1	1
21 Jan 2005	1	1
11 Sept 2005	1	1
14 Dec 2006	1	1
3) Multi-step FD (or complex FD)		
i) Multi-step FD in shock phase (with one or no step in MC phase)		
24 Nov 2001	2	1
ii) Multi-step FD in MC phase (with one or no step in shock phase)		
29 Oct 2003	1	3
26 July 2004	1	2
09 Nov 2004	1	3
15 May 2005	1	1
iii) Multi-step FD in both shock and MC phases		
24 Sept 1998	2	2
15 July 2000	2	2
06 Nov 2001	2	2

were used when data gaps were observed in OMNI data). The OMNI data are time-shifted from the spacecraft location to the Earth's bow-shock nose by considering the solar wind speed and the distance of the spacecraft from the bow shock (for more details, see http://omniweb.gsfc.nasa.gov).

The amplitude and profile of the observed FD generally vary with the energy of the CRs. Moreover, the neutron monitors are distributed globally with a varying geomagnetic cut-off rigidity, which provides an opportunity of studying FDs in different energy bands. To study the general energy variation, we categorized the neutron monitor data for each event into three categories: i) low rigidity ($0-2$ GV), ii) medium rigidity ($2-4.5$ GV), and iii) high rigidity (>4.5 GV). Furthermore, the average global response is studied using the mean neutron flux variation.

We used the boundaries of the shock sheath and the MC from the ICME catalog (Richardson and Cane, 2010), which is available at http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm. After careful inspection of the list, we found that two events occurred on 25 September 2001, and 17 January 2005 (out of a total of 18 events), for which the listed boundaries did not match the interplanetary disturbances given in the OMNI database. Therefore we excluded these two events from our investigation to avoid further confusion.

3. Observations

To understand the broad features of the FD profile, we classified the events based on the number of steps observed in CR flux corresponding to the shock sheath and the MC transit. The sharp variation is considered as a step when i) the amplitude of the CR flux variation is $\geq\sim 2\%$ and ii) it is observed in at least two rigidity windows. The quiet-time variation of the CR flux is generally of $\pm 1\%$, therefore we placed a threshold of $\sim 2\%$ to define the step. We note that the time over which the drop in count rate occurs can be different for different events, *i.e.* the FD step duration varies from event to event.

In addition, in all the figures we present here, the onset of the shock is shown by the first vertical black dashed line and the MC region is represented by the dashed rectangular blue box. The FD onset is determined by visual inspection when the neutron flux starts to decrease sharply. For every FD event, each step in the FD profile is indicated by black arrow-heads.

The details of these events with the proposed classification are presented in Table 1. The following subsections discuss a representative event of each classified category in detail. The remaining events are shown in the attached supplementary document.

3.1. One-Step FD (Caused by Shock or MC Phase)

The events that occurred on 13 July 2000, and 18 February 2011, represent one-step FD profiles, *i.e.* the CR flux shows a single step decrease during the ICME transit. Here, Figure 1 describes the representative event that occurred on 13 July 2000. The figure clearly shows that the onset of the FD observed in all neutron monitors is simultaneous with the arrival of the interplanetary shock sheath at the Earth's bow-shock nose. The arrival of the shock can be identified by the sharp enhancement in total IMF B and solar wind speed. The shock-sheath region lasted for ~ 3.3 hours (bounded by two dashed vertical lines from left). The overall gradual decrease is observed in the CR flux for all energies (top panel). It is important to note that the IMF components, particularly B_z, show fluctuations throughout the shock-sheath region. This might imply a turbulent magnetic field inside the sheath that causes the gradual decrease in CRs. As the Earth's magnetosphere encountered the MC, the neutron monitor flux continued to decrease gradually, reaching a minimum, and then it started to recover within the MC. We note that IMF B, V_{sw}, and plasma temperature steadily decreased and the plasma density remained almost steady, except for some variations.

We observed a single gradual decrease during the complete ICME transit, even though the *in situ* measurements clearly identified two regions of the ICME, *i.e.* the shock sheath and the MC. This observed single gradual decrease could be ascribed to a compound contribution from the shock sheath and the MC.

Similarly, the FD event that occurred on 18 February 2011, shows a single-step profile (we refer to the attached supplementary document). However, the shock sheath associated with this event shows a turbulent region just behind the shock-front that could have given rise to the observed decrease. During the later part of the sheath, the CR flux starts to recover. Interestingly, during the MC, the CR flux did not show an additional gradual or transient decrease, on the contrary, it continued the gradual recovery.

3.2. Two-Step FD (Caused by Shock and MC Phase)

The 16 strong events included 6 classical two-step FD events. These events show a first step transient decrease in CR flux during the shock sheath and a second step in the MC. These

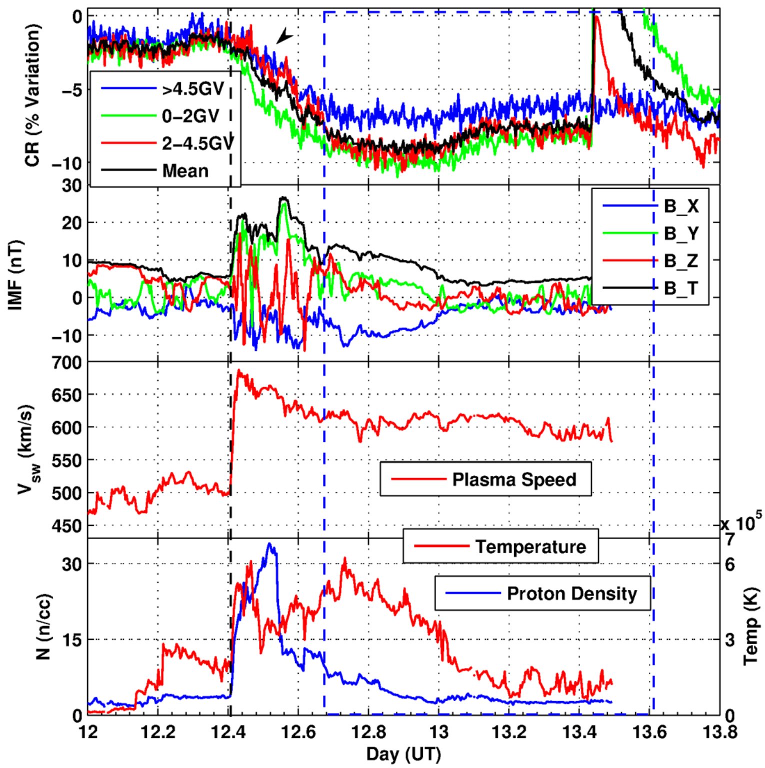

Figure 1 FD event on 13 July 2000. The *top panel* shows the temporal variation of the normalized neutron flux with the respective band of rigidities. The *arrow* shows the step decrease in CRs. The *second* and *third panel* show the interplanetary magnetic field (B_{Total} and B_X, B_Y, B_Z components) and solar wind speed data, respectively. The *bottom panel* shows proton density and plasma temperature variation. The onset of the shock is shown by the first *vertical black dashed line*, and the MC region is represented by the *dashed rectangular blue box*.

events include FDs that occurred on 17 September 2000, on 11 April 2001, on 22 January 2004, on 21 January 2005, on 11 September 2005, and on 14 December 2006.

Figure 2 shows the representative two-step classical FD event that occurred on 17 September 2000. The figure clearly shows that the onset of the first-step decrease observed in all neutron monitors is simultaneous with the arrival of the interplanetary shock. The shock-sheath region lasted for ∼4 hours. However, the first step decrease in CRs is observed only for ∼2 hours after the onset, followed by a recovery. This suggests that the first-step decrease in FD is caused by the shock-sheath component of the ICME. The second-step decrease started with the onset of the MC. This could be interpreted as a significant contribution of the leading edge of the MC to the second step of the FD. During the crossing of the remaining MC, a gradual recovery in CR flux is observed.

We note that the total IMF shows enhancement corresponding to each step decrease. Sharp fluctuations in the y- and z-components of the IMF are also observed. Here the first-step decrease could be interpreted as compression and a turbulent magnetic field behind the shock front. The second-step decrease appears to be associated with the onset of the MC. These observations support the current understanding of the classical two-step FD. It is intriguing that the CRs do not decrease during the complete transit of the shock sheath, but

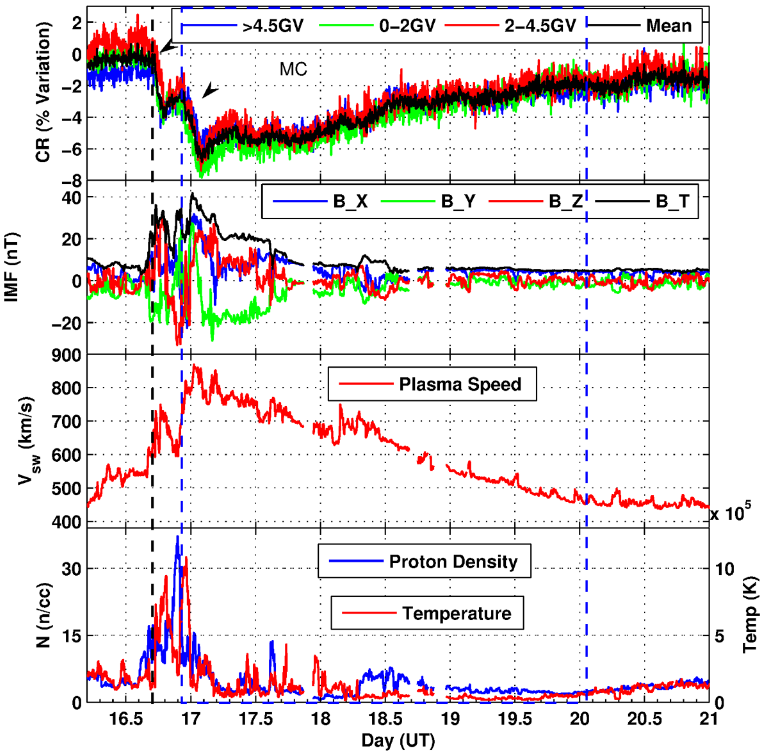

Figure 2 Forbush decrease event on 17 September 2000, in the same format as Figure 1.

recover after a sharp decrease within the shock sheath. However, this is not expected from the classical shock-barrier model (Wibberenz *et al.*, 1998).

All other events in this category show similar features (we refer to the supplementary materials).

3.3. Multi-step FD (or Complex FD)

As noted earlier, a one-step FD occurs when only the shock or only the MC crosses the observer, whereas a two-step FD occurs when both the shock and the MC transit the observer. However, the two-part structure of an ICME cannot immediately explain a multi-step or complex FD. Therefore, we define a new category as multi-step (or complex) FD in addition to the one-step or two-step FD categories. Furthermore, we may observe a multi-step FD profile during either the shock-sheath or/and the MC passing. Therefore, we need to extend the current FD classification based on the number of steps in the decrease observed in the FD profile during the shock sheath and the MC transit. In the following sections we examine events that have multiple steps in either the shock sheath, the MC, or in both.

3.3.1. Multi-step FD in Shock Phase (with One Step or with No Step in the MC Phase)

The complex FD events showing more than one step in the shock-sheath region and one step at most during the MC crossing are studied here. We observed only one FD event in this category. It occurred on 24 November 2001, and is shown in Figure 3.

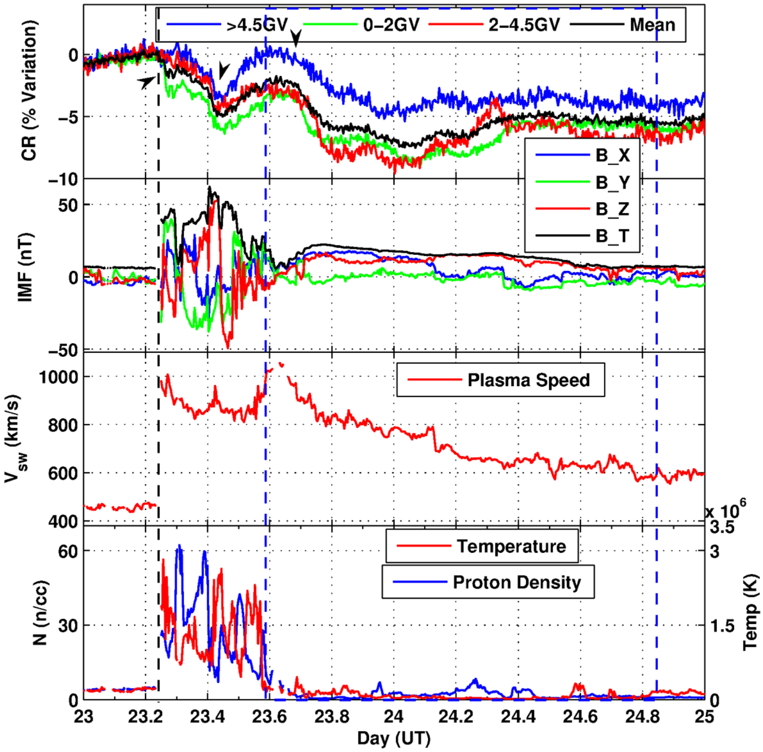

Figure 3 Forbush decrease event on 24 November 2001, in the same format as Figure 1.

The shock-sheath region lasted for quite long, ~ 7 hours. The first sharp step in CR flux is observed only in low-energy CRs (0 – 2 GV), but interestingly, it is absent in high-energy CRs. However, the CR flux of all energy windows shows a gradual decrease during the leading edge of the shock-sheath crossing. Interestingly, after ~ 2.7 hours from the shock onset, the CR flux shows a second sharp step decrease with a gradual recovery in all energy bands well within the shock-sheath region. Enhancements in total IMF B, are observed that correspond to each step decrease. As the Earth's magnetosphere encountered the MC, the CR flux remained steady, then further gradually decreased to its minimum. The remaining part of the MC contributes to the gradual recovery. The observed two-step decrease within the shock-sheath region is not expected based on the shock-sheath barrier model. All magnetic field components in the shock sheath highly fluctuate throughout the transit. We note here that even though the total IMF B is higher in the MC than the ambient IMF, it becomes lower for a small fraction of time (see the IMF values at 23.6 UT in Figure 3). Particularly after the shock-sheath crossing, the IMF intensity reaches a minimum of (< 5 nT) before it increases. This type of feature of the MC is not typical. However, it is possible that due to some uncertainty in the adopted ICME boundaries, this feature is ascribed to the MC rather than the shock-sheath region.

3.3.2. Multi-step FD in MC-Phase (with One Step or with No Step in the Shock Phase)

The FD events that at most show one step in the shock-sheath region and multi-step decreases during the MC transit are considered here. We observed a total of four FD events in

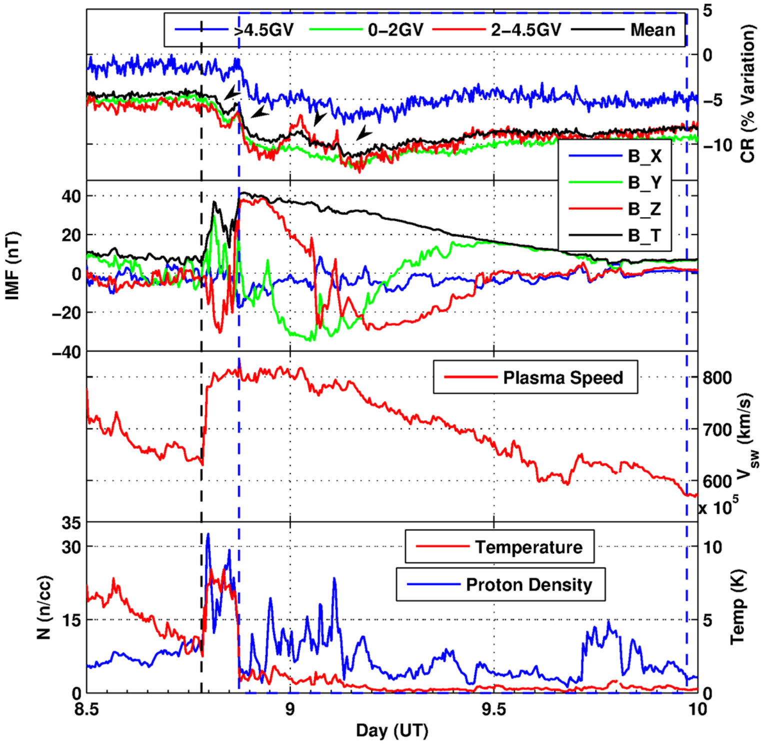

Figure 4 Forbush decrease event on 9 November 2004, in the same format as Figure 1.

this category, which occurred on 29 October 2003, on 26 July 2004, on 9 November 2004, and on 15 May 2005.

The representative event that occurred on 9 November 2004, is described in Figure 4. In this event the CR flux shows a gradual decrease followed by a small recovery during the shock-sheath transit. The total IMF and its components highly fluctuate, suggesting a compressed and turbulent magnetic field within the shock sheath. As the Earth's magnetosphere encountered the MC, the neutron monitors showed multiple sharp decreases in CRs. However, there are no sharp variations in total IMF B. A close inspection of the variations observed in the IMF components reveals sharp variations in the B_y and B_z components. This implies that the local spatial structures within the MC have given rise to the multi-step decrease for this event.

This event is a textbook example of the superposed effect of CR flux variations that are caused by broad substructures of the ICME (*i.e.* the shock sheath and the MC) and local spatial structures within these substructures. Similar multi-step features are seen in the remaining events, which are shown in the supplementary material.

3.3.3. *Multi-step FD in the Shock and MC Phase*

Forbush decrease events showing multiple step decreases in the shock sheath and in the MC are investigated here. We observed three events on 24 September 1998, on 15 July 2000, and on 6 November 2001.

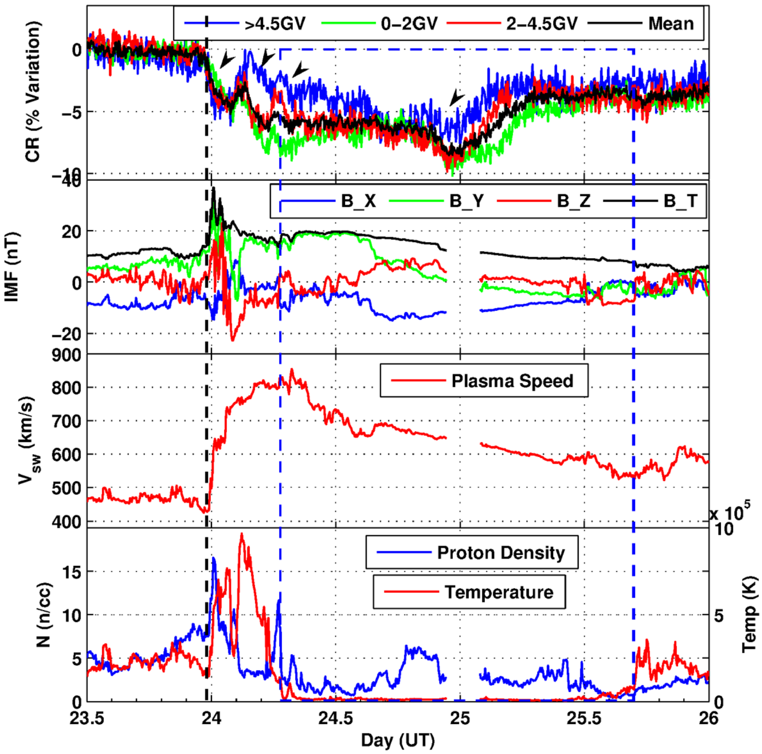

Figure 5 Forbush decrease event on 24 September 1998, in the same format as Figure 1.

The representative event occurring on 24 September 1998, is shown in Figure 5. There are two sharp decreases in the shock sheath and two more in the MC. The figure clearly shows that the onset of FD observed in all neutron monitors is simultaneous with the arrival of the interplanetary shock at Earth. The shock-sheath region lasted for ∼6 hours. It is observed that the sharp recovery (especially in high-energy CRs) in neutron flux occurs after ∼2.5 hours of the onset. The larger recovery in high-energy NMs compared to low-energy NMs is intriguing. After the sharp recovery in neutron flux, it starts to decrease again. During this second-step decrease, the IMF B and its components remained steady and the IMF was mainly oriented in the y-direction, *i.e.* dawn to dusk. We note that both these decreases occurred during passage of the shock sheath. Just before the arrival of the MC, there is a sharp recovery in CR flux. However, there is no sharp variation in the IMF that would correspond to this.

As the Earth's magnetosphere encounters the MC, the neutron monitor flux shows a minor sharp decrease and later remains low. Near day 25, there is a sharp decrease, and then a rapid recovery of CR counts is observed in all NMs. Unfortunately, the interplanetary data are missing during this period, so that we are unable to see the interplanetary signatures associated with this. The similar multi-step features related to the shock sheath and the MC are observed in other events of this category (we refer to the supplementary material).

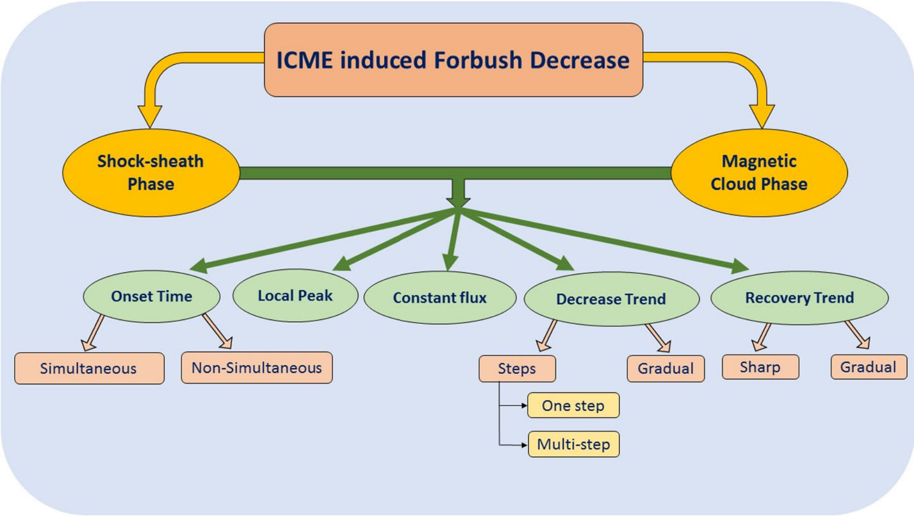

Figure 6 Summary of the general features in an FD profile caused by ICME transit. The shock sheath and the MC of an ICME are considered to be the real driver of the FD profile in the traditional model. However, the key features observed during the shock sheath and MC transit (as summarized in the above figures) cannot be explained by the traditional model. These features demonstrate the significant role of localized structures within the shock sheath and the MC in the FD profile.

4. Discussion and Conclusions

The transient variations observed in cosmic ray (CR) flux at Earth, which are known as Forbush decrease (FD), are understood as the diffusion of CRs through the ordered and turbulent large-scale interplanetary magnetic field (IMF). The highly asymmetric (*i.e.* sharp decrease and gradual recovery) and strong FDs are generally caused by interplanetary coronal mass ejections (ICMEs). These ICMEs typically have two substructures: a shock sheath (assumed to be turbulent), and a magnetic cloud (ordered structure) (Richardson and Cane, 2011; Vourlidas *et al.*, 2013). The generally accepted view is that the classical two-step FD has a first step due to the shock sheath and a second step due to the magnetic cloud (MC) (Raghav *et al.*, 2014). However, which part of the shock sheath and the MC gives rise to these steps is not well resolved. Therefore, understanding the role of local spatial structures within the substructures of ICMEs (shock sheath and MC) during an FD motivated the present study.

To address this issue, we have investigated 16 FD events of large magnitude. These events were further classified based on the observed number of sharp steps in the neutron flux time series during the shock sheath and the MC. During shock-sheath transit, we observed the following key features (summarized in Figure 6) of the FD profiles: i) one step, or multi-step decrease in CR flux, ii) simultaneous or non-simultaneous decrease with respect to the shock-front arrival at Earth, and iii) gradual decrease throughout the transit of the shock sheath or a short-duration sharp decrease corresponding to a small part of the shock sheath.

The absence of sharp CR decreases during the shock-sheath transit suggests a weak or less turbulent shock sheath. A one-step simultaneous FD indicates a strong turbulent shock sheath. The non-simultaneous FD indicates a weak shock-front with a localized turbulent sheath. The gradual decrease observed during the complete shock-sheath transit implies turbulence throughout the shock sheath. A short-duration sharp decrease corresponding to a small part of the shock sheath indicates turbulence in the local region of the shock sheath. The multi-step decrease in CRs could be due to multiple turbulent or enhanced magnetic field regions in the shock sheath (Arunbabu *et al.*, 2013; Raghav *et al.*, 2014; Subramanian *et al.*, 2009; Shaikh, Raghav, and Bhaskar, 2016).

This study also shed light on the role of MCs in the FD profile. A one-step decrease occurring during the crossing of the MC implies a sharply enhanced magnetic field in the MC. However, most of the events show a gradual decrease or nearly constant CR flux during the MC transit. This could be attributed to the inhibited diffusion of CRs within the MC as a result of an ordered magnetic field. Moreover, nearly all events show a recovery of CR flux within the MC. This could be ascribed to the declining total IMF B during the transit of the MC. As the IMF is decreasing, the diffusion of CRs into the MC increases, which results in the recovery of the CR flux (for example see Figure 2). The multi-step decreases observed during the MC transit could be due to the localized distortions of the ordered magnetic structure within the MC. Further detailed investigation of these local distortions is required to understand their origin. Interestingly, a few events show sudden enhancements (peak) in the CR flux just before the step decrease. The origin of this peak is beyond the scope of this article and will be studied in future work.

The ICME continuously interacts with the solar wind during its propagation in interplanetary space. Similarly, ICME-ICME or ICME-CIR interaction is also possible in certain conditions. This might result in fragmentation of the ICME or formation of complex structure, containing several shocks, stream-interfaces as well as MCs or MC-like structures (Khabarova *et al.*, 2015, 2016). This local spacial structure could be responsible for the observed single or multi-step variations in CRs during FDs. To resolve how these local structures affect the CR flux, their precise *in situ* identification is essential. However, the boundaries of ICME substructures (shock sheath and MC) identified using *in situ* measurements are ambiguous (for example consider the two online ICME catalogs http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm and http://space.ustc.edu.cn/dreams/wind_icmes/). This could be due to the fact that the satellite measurements are made *in situ* and might not represent broad regions of the ICME (Richardson and Cane, 2011). Therefore, it is a difficult task to exactly pinpoint the local structures within the substructures with reliable accuracy.

The current understanding of FDs separately considers the contribution of the shock sheath and the MC. Jordan *et al.* (2011) challenged this understanding and suggested the influence of small-scale interplanetary magnetic field structure in the FD profile. They concluded that the traditional model of FDs having one or two steps should be discarded (Jordan *et al.*, 2011). Observations of two-step FD profiles show agreement with first and second steps caused by the shock sheath and the MC transit, respectively, for six events out of studied 16 events, however. Moreover, events that occurred on 18 February 2011, 11 April 2001, and 13 July 2000, do not conform to the classic FD model, *i.e.* the FDs do not seem to have steps at the onset of the shock or else at the start of the MC. In addition, some steps correspond to the shock-sheath onset and the MC start even for multi-step FD events. Therefore, considering this, 13 out of 16 events ($\sim 81\%$) can be explained completely or partially on the basis of the classic FD model. However, we note that it cannot explain all the steps observed in these events. We therefore believe that the framework of the traditional model (which is quantified by Raghav *et al.*, 2014) can be retained. In addition, the observations of superposed multi-step CR variations over the classical FD profile (summarized features shown in Figure 6) cannot be explained by the traditional model alone. Observations suggest the need for an improved classification of FD events. Hence, we introduced a possibly better classification scheme for FD events, as outlined in Table 1. The multi-step decreases also demonstrate the significant role of localized structures within substructures (shock sheath and MC) in the FD profile.

In summary, not only large-scale substructures (shock sheath and MC) contribute to an FD, but also localized structures within the shock sheath and MC are important for the FD profile. Therefore, one needs to be cautious about these local structures when studying the relationship between FDs and ICME parameters. Moreover, accounting for the influence of these local structures is essential for an accurate modeling and understanding of CR transport in the heliosphere.

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