Exploring the common origins of the Forbush decrease phenomenon caused by the interplanetary counterpart of coronal mass ejections or corotating interaction regions

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(Received 26 June 2019; accepted 18 February 2020; published 24 March 2020)

The interplanetary counterpart of coronal mass ejections (ICMEs) and the interaction regions of slow-fast solar wind (CIRs) have both been known as potential drivers of Forbush decrease (FD). However, reported studies often take an independent approach for investigating FD caused by ICMEs and CIRs, since both the structures show different signature in in-situ observations. In this paper, we explore the common origin of the FD profile caused by these two large scale structures, within the framework of a diffusion-convection model. As a case study, we present one event of each type, in both of which, the solar wind is the most prominent driver. Possible extensions of this model could incorporate other parameters such as magnetic field strength, turbulence, etc which influence the observed FD features. This attempt could help to resolve the complex problem of the diversity in observed FD profiles.

DOI: 10.1103/PhysRevD.101.062003

I. INTRODUCTION

Our planet Earth and its atmosphere are being constantly bombarded by massive, energetic particles/rays known as cosmic rays (CRs) from anywhere beyond its atmosphere. Their interaction with the Earth's upper atmosphere produces a shower or cascade of secondary particles out of which neutrons and muons are observed across the globe by ground based neutron monitors or muon telescopes [1,2]. Therefore, in general, the muons and neutron flux measured by their respective observatories worldwide are considered to be a good proxy for actual cosmic ray flux entering the top of the atmosphere. The temporal variation in secondary cosmic ray intensity at the Earth sometimes shows a decrease and corresponding recovery which typically last for about few days, known as Forbush decreases (FDs) [3–6].

Simultaneous measurements of ground neutron monitors as well as *in-situ* interplanetary magnetic field and plasma parameters have helped to probe the general underlying physical phenomenon for FDs.(e.g., [4,5,7–9]. The Forbush decreases are typically caused by (i) the substructure of interplanetary counterparts of coronal mass ejections (ICME) [4–6,10–14] known as "magnetic cloud (MC)/ejecta" and "shock" and (ii) corotating interaction regions (CIRs) [3,7,15–19]. Based on causal agent, Forbush decrease events are divided into two basic categories; (a) nonrecurrent FDs caused by ICMEs and (b) recurrent FDs caused by CIRs. The former type show a sudden onset, reach maximum depression within about a day and have a more gradual recovery. On the other hand, the latter have a more gradual onset with almost similar duration recovery making a symmetric profile.

A majority of nonrecurrent FDs show one/two step decrease. Generally, it is believed that the first step is due to the shock (including sheath) and the second is due to the MC [4,5,20]. It has been reported that decrease and recovery due to shock are more gradual and symmetric in profile, whereas MC have a sharp decrease and fast recovery [21]. The cross-correlation studies [13,14,22–28] have reported a good correlation between the amplitude of FD and corresponding amplitude and duration of the interplanetary magnetic field and solar wind speed. Comparisons with white-light coronagraphic observations have also found the FD magnitude to be larger for (i) faster CMEs [25,26,29], (ii) CMEs with larger apparent width [26,30], and (iii) CMEs with greater mass [26]. The energy dependence of the FD amplitude [4,31] and

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its recovery time [32,33] suggest that the strength of the modulation, the amplitude of the FDs, and the recovery time are anticorrelated with the cosmic ray energy.

The independent contribution of shock and MC to Forbush decrease is taken into account by classical two-step FD model. The first step of FD is connected to the turbulence structure behind the shock, and the second step is connected to the enhanced magnetic field and looplike field configuration of the ICME, i.e., MC [4,5,21,34,35]. The shock only model assumes the diffusion of cosmic rays across the propagating diffusive barrier [21,36]. Right behind the shock-front solar wind velocity and magnetic field enhances which can reduce the drift of cosmic rays. The contribution of turbulence associated with shock sheath in energy dependence of shock phase FD amplitude has been quantified in earlier works [5,20,21,37,38]. In addition, the ejecta effect has been also discussed in terms of a simple model in which particles gain entry in to the ejecta via perpendicular diffusion [39]. In a few studies, the turbulence ahead of the front-edge of MC was assumed which led to the Forbush decrease due to the difference between the cosmic ray density inside and outside the magnetic cloud crossing the Earth [5,37,38].

Besides this, Raghav *et al.* (2017) [6] studied 16 Forbush decrease events of large magnitude caused by ICME. They pointed out the inadequacy of classical model for the two-step FD, emphasising complexity in FD profiles during shock-sheath and MC transit such as no step or one step or multistep decrease, simultaneous/nonsimultaneous decrease with respect to the shock-front/MC arrival at the Earth, a gradual decrease or short-duration sharp decrease etc. The presence of small-scale magnetic structure within the shock-sheath of ICME is clearly identified [40–42], emphasizing the importance of their influence on cosmic-ray variations.

The interaction of high-speed solar wind stream originating from a coronal hole at the Sun with the preexisting slower solar wind formes a stream corotating interaction regions (CIRs) [15,17,43–46]. Most of the CIRs are bounded by magnetohydrodynamic fast forward and reverse shock pairs [45], which extend to 1 AU for around 31% of the CIRs [47]. Forward shock is characterized by the sharp increases in speed, density, temperature and magnetic field magnitude, while in the case of reverse shock, there is a sharp increase in speed but decreases in the other parameters [28,45]. The CIRs with a forward shock is more effective in CR depression amplitude as compared to CIR without shock, even though the time profiles of CR variation is similar in both the cases [48]. Physical mechanisms considered to understand the cause of cosmic ray decrease onset include: solar wind speed increases at stream edges, magnetic sector boundaries, magnetic field enhancements, and stream interfaces [16]. However, in some cases, it appears that the cosmic ray flux profile was not affected by magnetic field configuration [44]. In addition, the anticorrelation between solar wind speed and cosmic ray intensity is a remarkable feature associated with many fast streams/CIRs. To elucidate this, Richardson *et al.* (1996) [7] proposed that the enhanced convection of cosmic rays from the inner heliosphere in high-speed streams may contribute to cosmic ray decrease. They modeled this process using a steady state diffusion-convection model including adiabatic deceleration and longitudinal variations in the solar wind speed. Recently, Bhaskar *et al.* (2016)[49] enforced the same model to explain the recovery phase of the ICME induced Forbush decrease profile.

Cosmic ray modulation was explained in general by a transport equation which accounts for the diffusion, convection of solar wind, gradient, and curvature drifts arising because of the magnetic field, and energy change due to compression or expansion of the fluid [50,51]. The last few decades have seen various theoretical models proposed to explain the various characteristics of the FD profile. The number of physical processes such as diffusion [52,53], diffusion-convection [7,49,54,55], guiding center drift [56–58] and energy change [59,60] form the foundation for the proposed models. On the other hand, models based on ordered and/or turbulent magnetic fields in the interplanetary medium, convection and adiabatic energy loss by a fast stream, enhanced drift as well as scattering properties of a strong and fluctuating magnetic field, effect of finite Larmor radius, etc. [5,8,20–22,36–38,58,61–67] are also considered to understand the FD.

These early investigations sow the seeds of “cosmic ray modulation” research. This phenomenon is highly complicated to study due to dynamic space weather conditions in interplanetary space. In light of earlier studies, we opine that the cosmic rays may respond to the changes in the solar wind speed, turbulence, and magnetic field intensity. Moreover, the observations will allow us to infer which processes may be more important than others.

As described above, the two independent causes for FD, *viz.* ICME and CIR, which also lead to very different signatures in the in-situ interplanetary parameters (e.g., [4,16,18,68]) as well as cosmic ray intensity variations have traditionally been treated separately in the literature. To our best knowledge, no significant efforts have been made to provide a unified approach to explain the FD originating from ICME and CIR. Here, we provide a proof-of-concept for a unified semi-empirical model, which utilizes the same parameters to explain FD events arising from ICME as well as CIR. It would be expected that a detailed formulation of the present model, including all major interplanetary parameters, would be able to explain all aspects of observed CR modulations.

II. EVENTS, DATA AND METHODS

We have selected the following two Forbush decrease events for the present study:

(1) 17 Sep 2000 (ICME induced).

(2) 05 Feb 2000 (CIR induced).

As enumerated above, there are various underlying physical mechanisms (such as diffusion-convection of the solar wind, magnetic field effects, and fluid dynamic effects) which contribute in the overall FD profile. However, in some cases, one of the mechanism may be dominant over others. For example, (i) solar wind speed and cosmic ray intensity shows anti-correlation in high-speed streams [7], (ii) In ICME point of view, Bhaskar *et al.* (2016) suggest that the solar wind speed play crucial role in recovery phase of ICME induced FDs [49]. Therefore, in the present case study, the two FD events have been selected by us—one each caused by an ICME and a CIR respectively—in which

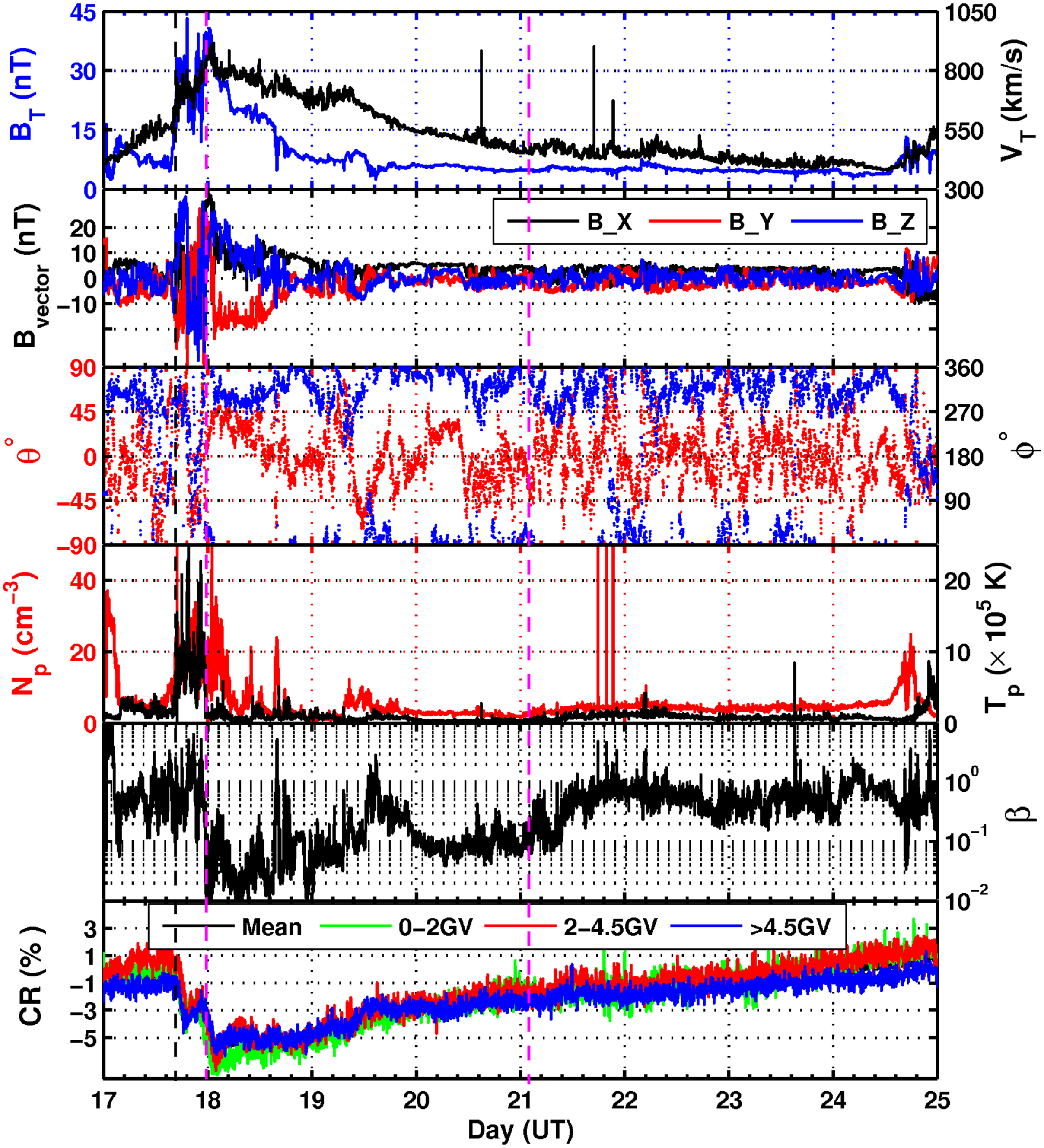

FIG. 1. The interplanetary magnetic field (IMF), solar wind plasmas, and neutron intensity observations of classical two-step Forbush decrease event caused by ICME which crossed the WIND spacecraft from 17 September 2000. The first panel from top show the total magnetic field strength ($|B_T|$) and solar wind speed (V_{SW}), the second and third panel show vector components of the magnetic field and the elevation (theta) and azimuthal (phi) of field direction in GSE coordinate system, the fourth panel shows proton density (N_p) and proton temperature (T_p), the sixth pane shows the ratio of proton thermal pressure to magnetic pressure (β) and the bottom panel shows the temporal variation of normalized cosmic ray intensity in different energy bands. The black vertical dash line indicates the onset of shock whereas the pink vertical dash lines depict the boundaries of a magnetic cloud.

diffusion-convection mechanism induced by solar wind is dominant compared to magnetic field. Here, particularly we have selected well discussed ICME event from Bhaskar *et al.* (2016) study [49].

The 92-seconds time resolution Wind satellite data of interplanetary magnetic field and plasma parameters are utilized to study the characteristics of the corresponding ICME and CIR events. The wind database is available at https://wind.nasa.gov/data.php. To study the cosmic rays response to both these interplanetary disturbances, we have analyzed the neutron intensity data from various neutron monitor (NM) observatories which are available at Neutron Monitor Database, i.e., nest. nmdb.eu. Considering variations of local characteristics and baseline value in each neutron monitor observatory, we have performed normalization process. The normalized percentage variation (%) for each Neutron monitor observatory is defined as

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

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. Classification of neutron monitor data was done into three broad energy band, (i) low rigidity (0–2 GV), (ii) medium rigidity (2–4.5 GV) and (iii) high rigidity ($\geq$ 4.5 GV). The presented data for each energy band is the average normalized neutron flux of all observatory comes under a given energy band.

A. ICME induced FD event

In general, the Forbush decreases caused by an ICME are observed to be one-step or two-step. Here, we investigate prototype of classical two-step FD event occurred on the September 17, 2000 as shown in Fig. 1. The sudden enhancement in total interplanetary magnetic field, i.e., IMF (B_T), solar wind speed (V_T), plasma density (N_p) and plasma temperature (T_p) indicates the arrival of shock-front whereas sudden decrease in T_p and plasma β values (ratio of thermal-to-magnetic pressure) indicate the front edge of magnetic cloud arrival. The shock-sheath regions display the high fluctuations in B_T, all components of $\mathbf{B}$ and the elevation and azimuthal orientation of field direction as well as high values of N_p and T_p. Moreover, the magnetic cloud shows a gradual decrease in B_T and N_p as well as low T_p and β values. The onset of the first step and two-step decrease observed in all energy band are coinciding with the crossing of interplanetary shock and magnetic cloud respectively. The complete shock-sheath crossover took ~4 hours, however, the corresponding decrease in cosmic ray intensity is observed only for ~2 hours after the onset and later it shows recovery. However, this is not expected from the shock-barrier model [21]. Similarly, the leading edge of MC contributed in the second step FD whereas the trailing portion of MC corresponds to recovery in cosmic ray intensity. The total IMF and solar wind show enhancement corresponding to each step decrease. This observation supports the present understanding of classical two-step Forbush decreases.

B. CIR induced FD event

The symmetric low amplitude Forbush decreases are generally evoked by CIRs. The prototype of such Forbush decrease event occurred on the February 05, 2000 as shown in Fig. 2. The gradual enhancement of B_T and V_T are seen. The high fluctuations are also observed in the components of $\mathbf{B}$ as well as in the elevation and azimuthal orientation of field direction. The high plasma proton density is observed in the initial part which gradually decreases in the rest of the CIR regions. The plasma temperatures remain high which indicates the signature of interacting regions. The β value is fluctuating near ~1. The cosmic ray intensity depicts nearly ~2% of gradual decrease in all energy bands which are superimposed by diurnal variations.

III. MODEL DESCRIPTION

The various observational studies have shown a remarkable anticorrelation between solar wind speed and cosmic ray intensity. To account for this, the diffusion-convection model was proposed by Richardson *et al.* (1996) [7]. They suggested that CIRs associated FDs are induced by the enhanced solar wind convection. Based on this model, Bhaskar *et al.* (2016) [49] utilized the following equation, which relates the depression in particle counts to variations in the solar wind speed:

$$\frac{\partial U}{U} = -3CN\frac{\partial V_{sw}}{c} \tag{2}$$

where, C is the Compton-Getting factor, U is the cosmic ray density, V_{sw} is the solar wind speed, and N is the number of mean free paths of cosmic ray. This equation directly relates the cosmic ray intensity decrease to the solar wind speed (V_{sw}). The speed of light in free space is represented by c. The detailed description of the force field approximation model is described by [69,70] and reference therein. The value of C was taken as 1.8 by Bhaskar *et al.* (2016) [49].

The model takes N as a free parameter. We allow N to vary from 1 to 50, and compare modeled cosmic ray intensity to the observed cosmic ray intensity for each FD event. The χ^2 minimization technique is used to obtain the best fit value of the N parameter.

A. Application of the model to ICME induced FD event

The two-step classical FD event occurred on September 17, 2000, is caused by an ICME (see Fig. 1). The strong correlation is observed between solar wind speed and the cosmic ray intensity in the recovery phase of the FD. The

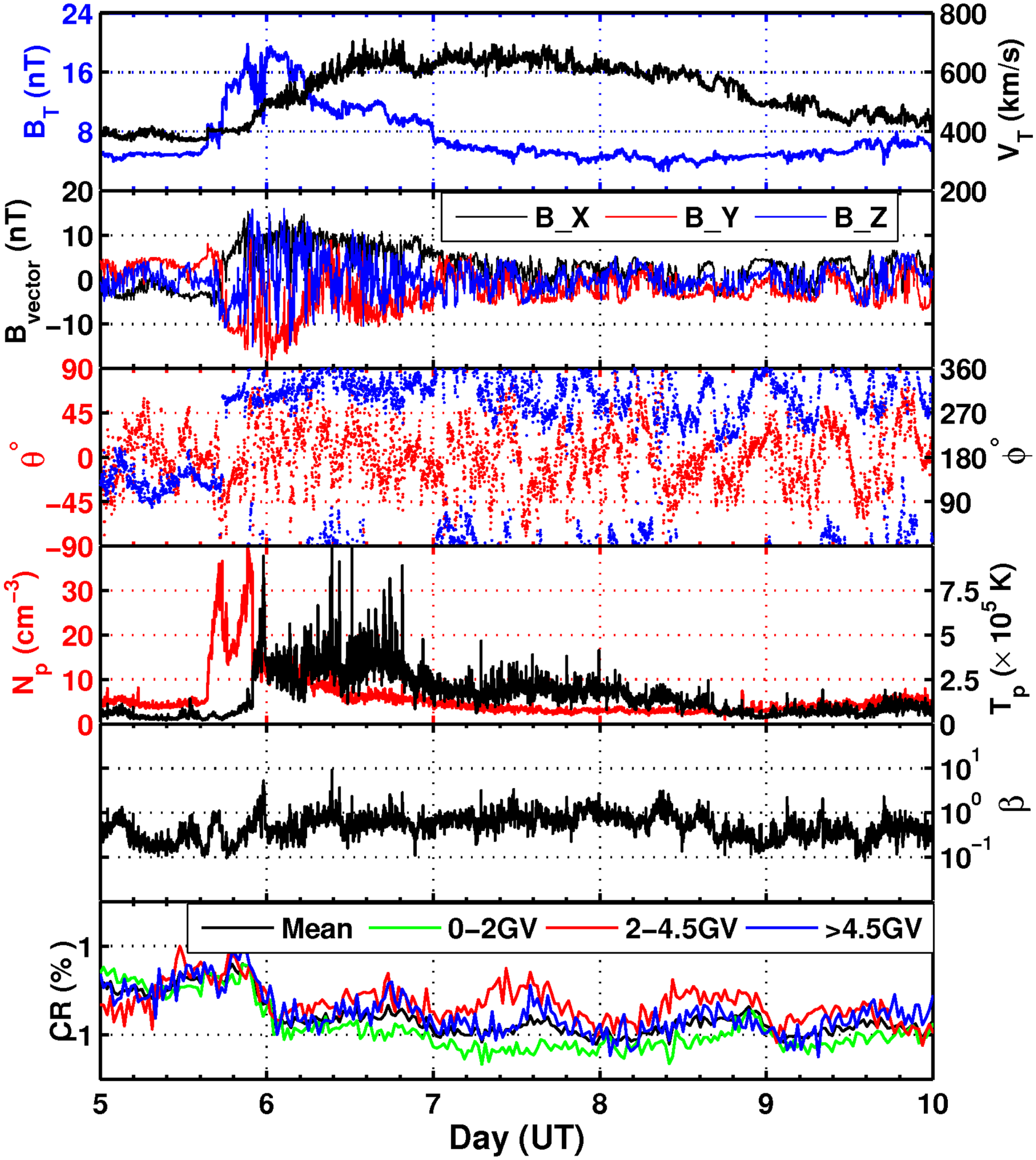

FIG. 2. The interplanetary magnetic field (IMF), solar wind plasmas, and neutron intensity observations of a Forbush decrease event caused by CIR which crossed the WIND spacecraft from 05 February 2000. All panels are arranged as mentioned in Fig. 1.

above-discussed diffusion-convection model is used to explain the recovery phase of the FD [49,71]. Here, we utilized the same model to account for both the decrease and recovery phase of a FD profile as shown in Fig. 3.

The Fig. 3 shows the temporal variation of low energy band (0–2 GV) neutron intensity data (blue), and diffusion-convection model [Eq. (5)] output after χ^2 minimization (black and red). The average value of solar wind speed before ICME onset and after ICME crossover is different (see Fig. 1). Therefore, the model described in Eq. (5) is implemented using two different background values of speed, corresponding to main (region 1) and recovery (region 2) phase. In the region 2 (shown as black fitted curve), we estimate the cosmic ray intensity variation by taking 400 km/s as a base value of the solar wind speed (V_{sw}). Figure 3 (left) demonstrates that the model output is well correlated (in fact it almost exactly reproduces the observed profile) with the observed cosmic ray intensity during the recovery phase of the FD. In this case, the procedure yields $N = 9$ (right plot of Fig. 3). In the region

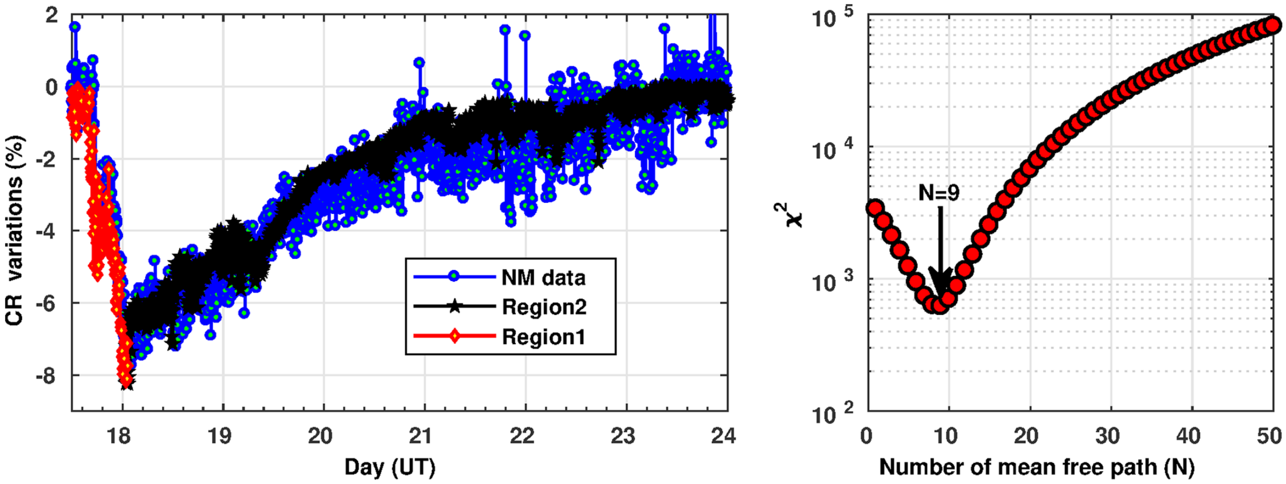

FIG. 3. Left: Diffusion-convection model output comparison with observed ICME induced FD event occurred on 17 September 2000. Right: χ^2 variations associated with the number of mean free paths.

1, the 530 km/s as a base value of the (V_{sw}) is used. The estimation using the model indicates an excellent match with observed FD profile during the main phase. In this region, the procedure yields $N = 12$ (not shown here). We note that the model output could be affected by the base value (background) of the chosen solar wind speed.

B. Model application for CIR induced FD event

A typical CIR induced FD event occurred on 5 February 2000 (see Fig. 2). Here, we employ the same model to explain CIR caused FD event observed by the Earth-based neutron monitors. Figure 4 (left) illustrate the model output (red star) and the measured cosmic ray intensity variation (filled magenta with blue circle). The model closely reproduces a CIR induced FD. The right side plot of the figure gives the information obtained from the χ^2 minimization technique which determines $N = 3$.

IV. DISCUSSION AND CONCLUSIONS

ICMEs and CIRs have been proposed in the literature as the primary potential drivers of FD phenomena. However, based on the observational indications, separate approach has been taken while discussing FDs caused by ICMEs and CIRs due to their distinguishable signature in *in-situ* data. At the same time, it is important to note that the primary physical mechanism for cosmic ray modulation, i.e., diffusion, convection, gradient, and curvature drift of the cosmic ray particles [50,51], are common factors to both of these large scale solar wind structures (ICMEs and CIRs). Therefore, it would be an attractive proposal to find a common underlying approach to these two seemingly diverse phenomena.

It is clearly noticeable from Fig. 3 and Fig. 4 that the model mimics the complete phase of the FD profile in both the cases i.e., ICME and CIR induced FDs. This does not

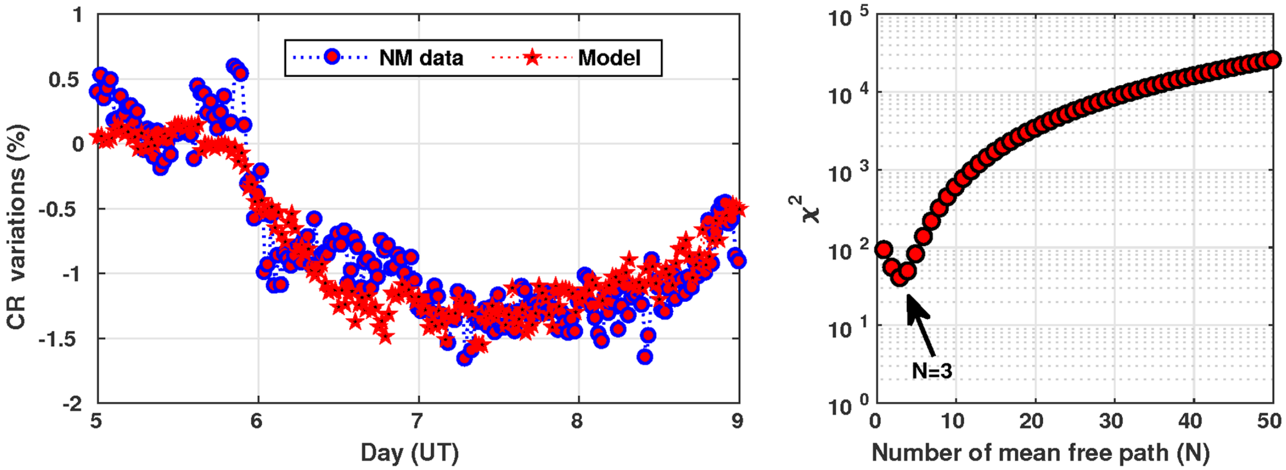

FIG. 4. Left: Diffusion-convection model output comparison with observed CIR induced FD event occured on 5 February, 2000. Right: χ^2 variations associated to number of mean free paths.

imply that the magnetic field contribution is less important in causing the modulation of CR. It only manifests that for the selected events in our study, solar wind speed is playing a major role in cosmic ray intensity modulation as compared to other factors.

The diffusion-convection model with χ^2 minimization technique provides an estimate of the number of mean free paths of cosmic rays spanned by the large scale structure which is causing the FD. For the selected ICME induced event, we estimate $N = 12$ (corresponding to main phase of FD) and $N = 9$ (corresponding to recovery phase of FD), while for CIR induced event $N = 3$ reproduces the observed variations in the CR counts over the entire region studied. Since the solar wind speed gradient is the factor affecting the mean free path of the cosmic rays in the model, the estimated value of N suggests that lower solar wind speed gradient is responsible for the higher estimates of the number of mean free paths. The model estimation indicates that the N value for an ICME induced event is 3 to 4 times higher than that obtained for a CIR induced event. It is clear that the mean free path of cosmic rays is a key parameter for the transport. However, in a more general case, the contributions of other parameters can not be overlooked.

One can determine the possible value of the mean free path of cosmic rays and further examine whether the estimated N is consistent with observations or not. For the ICME event, we observed approximately 7.5 days of disturbed period with an average speed of disturbance as 700 km/s. In this scenario, the mean free path for CR is estimated to be 0.25 AU for $N = 9$ and 0.34 AU for $N = 12$. For the CIR event, the disturbed conditions are observed for approximately 3 days with an average solar wind speed of 650 km/s which leads to an estimate mean free path 0.375 AU for $N = 3$. The estimated mean free path values of cosmic rays in our study are consistent with the observed mean free path, i.e., ~0.30 AU at a radial distance of $1AU$ by Bieber *et al.* (1994)[72]. This is also of the same order as the estimate of Hamilton (1977) [73], who obtained $\lambda \sim 0.25$ AU at 1 AU, by assuming $\lambda \propto r^{0.4}$. Also, [7] reported similar values of the mean free path for FDs associated with CIRs using spacecraft's safeguard data.

In conclusion, in this paper, we have considered two FD events (one each of ICME-induced or CIR-induced type) which are dominated by diffusion-convection. The model used in the present study is able to explain all the features of the studied FD events independent of the specific origin. This common model approach to the FDs, which are traditionally treated as separate in the literature based on their origin, may throw some light on the physical mechanisms responsible for FD phenomena in general. An inclusion of magnetic field strength parameters and turbulence in such a model could lead to a complete understanding of the underlying processes.

Future studies may focus to identify the properties in the plasma observations which affects the mean free path of CRs particles. Also, *in situ* observations of ICME or CIR is limited to only single point measurements and overcoming this may provide additional information on the spatio-temporal variations of fluctuations in solar wind structures. A better understanding of FDs would be achieved if more knowledge on the temporal dependence of diffusion coefficients, different features of solar wind structures, and magnetic field turbulence are acquired.

ACKNOWLEDGMENTS

We are thankful to WIND Spacecraft data providers (wind.nasa.gov) for making interplanetary data available. We are also thankful to Department of Physics (Autonomous), University of Mumbai, for providing us facilities for fulfillment of this work. A. B. is supported by the NASA Van Allen Probes Mission.

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