Analysis of Galactic Cosmic Ray Forbush Decrease: Case Study of Five (5) Forbush Decrease Events

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Abstract: ***The short - term variation of galactic cosmic ray (GCR) flux caused by interplanetary coronal mass ejections (ICMEs) and their associated shocks or magnetic flux ropes is known as Forbush decrease. This temporary decrease in the flux of galactic cosmic rays (GCRs) is observed at earth by NMs at locations that were possibly passed by the ICME depending on the station's viewing direction. This research investigates five specific occurrences of Forbush Decrease (FD) events and their impact on Galactic Cosmic Ray (GCR) flux. This entails scrutinizing the magnitude and length of the decreases and also taking into account the corresponding solar activity indicators. In order to quantify the temporal profiles of GCR flux throughout each occurrence, we analysed data from worldwide network of Neutron Monitors (NMs) and modelled the magnitude of decrease for each event selected. Interestingly, we found that the magnitudes of Forbush decrease D (t) can be used to detect the arrival of an ICME and to explain the characteristics of Forbush decreases. Secondly, we observed that Forbush decrease caused by shock and or ejecta due to the arrival of an ICME are detected by all polar NMs at the same time and also show similar characteristics excepts for the distinct differences in recovery times. The time of arrival at earth and magnitude of decrease may vary depending on viewing direction of the station. our results have provided valuable guidance for future investigations of Forbush Decrease.***

Keywords: Cosmic Rays, Forbush decrease, ICME, Neutron Monitors

1. Introduction

The relationship between the Sun and Earth environment is crucial given how it shapes diverse aspects of our planet - specifically with regards to its atmospheric physics. One intriguing consequence that stems from this connection is how Galactic Cosmic Rays (GCRs) are modulated resulting in fluctuations observed at Earth's surface known as Forbush Decreases (FDs) [1, 2].

Comprehending the traits, processes, and consequences of Forbush Decreases carries great significance for numerous reasons. Firstly, these decreases can provide valuable insights into the intricate interplay between the Sun, interplanetary space, and Earth's magnetosphere. By analysing FD occurrences, scientists can obtain important knowledge regarding solar phenomena's dynamics and their impact on Earth's space environment [3].

Another point to consider is how Forbush Decreases could impact Earths atmospheric physics and climate. These occurrences trigger fluctuations in GCR levels which can cause changes in atmospheric ionization – having an effect on cloud formation specifically. This can ultimately cause alterations in Earths radiative balance. Research into how these events impact important climactic processes is essential if we are to gain a fuller understanding of long - term variability in our planet's climatic patterns over time [4].

In the field of space weather, there is much interest in Forbush Decreases. These occurrences can cause fluctuation in GCR flux thus disrupting communication systems and satellites functioning in space. By investigating these episodes, experts are working to enhance their predictive abilities regarding potential impacts on technological infrastructure [5].

These flux changes have been subjected to extensive investigation due to their possible impact on GCRs [6]. For example, Scott E. Forbush [7] pioneered research on what is now known as Forbush Decreases - a phenomenon that captures temporary blips in (GCR) levels detectable at earth. Typically triggered by energetic emissions from our Sun - such as solar flares or coronal mass ejections (CMEs) - these fluctuations occur when these particles reach our planet and encounter its magnetosphere. The magnetic fields of CMEs can alter the trajectory, speed and distribution of GCRs that subsequently reach us on the ground; this results in detectable dips in GCR flux during FD events.

Consequently, Wawrzynczak and Alania (2010) [8] examined the Forbush decrease of the GCR intensity observed on 9 - 25 September, 2005 using experimental and a newly developed time - dependent three - dimensional model and found that the changes of the rigidity spectrum exponent does not depend on the level of convection ofGCRs stream by the solar wind.

Similarly, Wawrzynczak and Alania (2007) [9] studied the temporary changes of the rigidity spectrum of Forbush decrease effect of GCR intensity and observed that variations of GCR intensity during FDs are generally shaped by the temporal changes in the interplanetary magnetic field turbulence.

Furthermore, Zhao L. - L. and Zhang. H. [10] carried out a comparative analysis of two prominent FD events during cycle 24 occurring on March 18 2012 and 22 June, 2015 and found that the two events showed differences in terms of energy dependence and recovery time.

Additionally, Cane (2000) [11] showed that a FD can be caused by both shock and ejecta or shock only. In a case of both shock and ejecta, it is called classical two - step F. D.

Appropriately, the main objective of this research paper is to analyse five particular instances involving Forbush Decrease events. Our primary focus will be on examining their distinctive traits, and their potential effects on GCR flux. Through analysing multiple case studies that highlight these occurrences' behaviours and variables, we aim to foster a holistic comprehension about their contribution towards the creation of predictive models whilst enhancing space weather forecasting ability. Thus, we modelled the magnitude of Forbush decrease for 5 candidate events and compared our results with available Forbush decreases observed at earth by different neutron monitors. We find that the magnitudes of Forbush decrease D (t) can be used to detect the arrival of an ICME and to explain the characteristics of Forbush decreases. Secondly, we observed that Forbush decrease caused by shock and or ejecta due to the arrival of an ICME are detected by all polar NMs at the same time and also showed similar characteristics excepts for the distinct differences in recovery times. The time of arrival at earth and magnitude of decrease may depend on the viewing direction of the station.

2. Methods

A theoretical approach was used to model Forbush decrease $D(t)$ for each event. To determine $D(t)$, we first normalized the count rates of each event to pre-Forbush decrease level (that is a day or few hours before the event occurred). For example, this is taken at the second half of day 13 is for the April 2013 event.

Thus, $D(t)$ is modelled after normalization using(modified from [6]):

$$\frac{P_t(t)}{1} = \frac{\sum_{l=0}^{8} w_l \int_{P_{\min,n,l}}^{P_{\max}} \left(\frac{-dN(P_c)}{dP_c} \Big|_P \right) T_{n,l}(P) \frac{P}{D(t)+P} dP}{\sum_{l=0}^{8} w_l \int_{P_{\min}}^{P_{\max}} \left(\frac{-dN(P_c)}{dP_c} \Big|_P \right) dP}$$

(1)

here, we begin the integration from $P_{\min} = 1GV$ because we are considering only polar stations and similarly transmission function $T = 1$, $P_{\max} = 1000GV$. The differential response function $dN(P)$ is $N_0 \alpha P^{-\kappa-1} \kappa \exp(-\alpha P^{-\kappa})$, where $N_0 = 29.70, \alpha = 9.57, \kappa = 0.903$ and P_t = average normalized count rate of all polar NMs. Integration of equation (1) is done using Simpson's rule for analytical functions and the results obtained from this analysis is presented in section 3.

2.1 Data Information

We used data from polar NM stations with good statistics and no major data gaps during the period of FD. These stations and their geographic locations along with their geomagnetic cutoff rigidity are presented in table1 (Modified from [6]). The neutron monitor data were obtained from the Neutron Monitor Database [http://www.nmdb.eu]. We used data from all available polar stations in this database of the worldwide network of neutron monitors with good data for the time period considered.

Table 1: Sources of Neutron Monitor Data

S/N	NM Location	Station Code	Geographic Latitude (deg)	Geographic Longitude P_c (GV)	Cutoff Rigidity P_m (GV)
1	Thule, Greenland	TH	76.50	- 68.70	0.00
2	Fort Smith, Canada	FS	60.02	- 111.93	0.00
3	Peawanuck, Canada	PE	54.98	- 85.44	0.00
4	Barentsburg, Russia	BA	78.06	14.21	0.00
5	McMurdo, Antarctica	MC	- 77.90	166.60	0.00
6	Terre Adelie, Antarctica	TA	- 66.55	140.00	0.00
7	Nain, Canada	NA	56.55	- 61.68	0.01
8	South Pole, Antartica	SP	- 90.00	0.00	0.09
9	Inuvik, Canada	IN	68.36	- 133.72	0.18
10	Mawson, Antarctica	MA	- 67.60	62.87	0.22
11	Jang Bogo, Antarctica	JB	- 74.62	164.23	0.30
12	Tixie Bay, Russia	TB	71.36	128.54	0.48
13	Norilsky, Russia	NO	69.26	88.05	0.58
14	Apatity, Russia	AP	67.57	33.40	0.65
15	Oulu, Finland	OU	65.05	25.47	0.81
16	SANAE, Antarctica	SA	- 70.32	- 2.35	1.06
17	Kerguelen, near Antarctica	KE	- 49.35	70.25	1.14

3. Results

The results presented here are from the analysis of the following Forbush decrease events: 18 February 2011, 8 February 2014, 13 April 2013, 16 June 2012 and 31 December 2015. Results of the analyses are presented in figures (1) to (5).

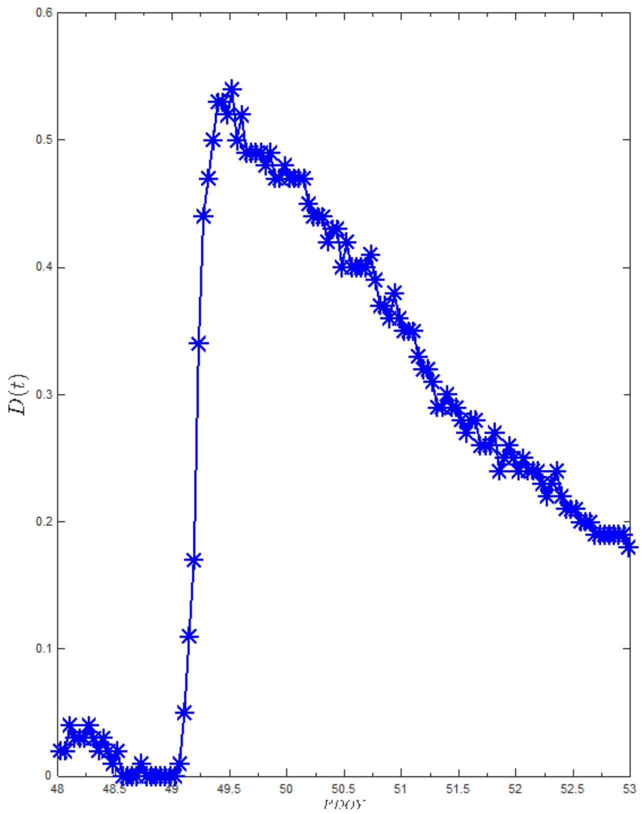

Figure 1 (a): Forbush Decrease magnitude (D) for the February 2011 event.

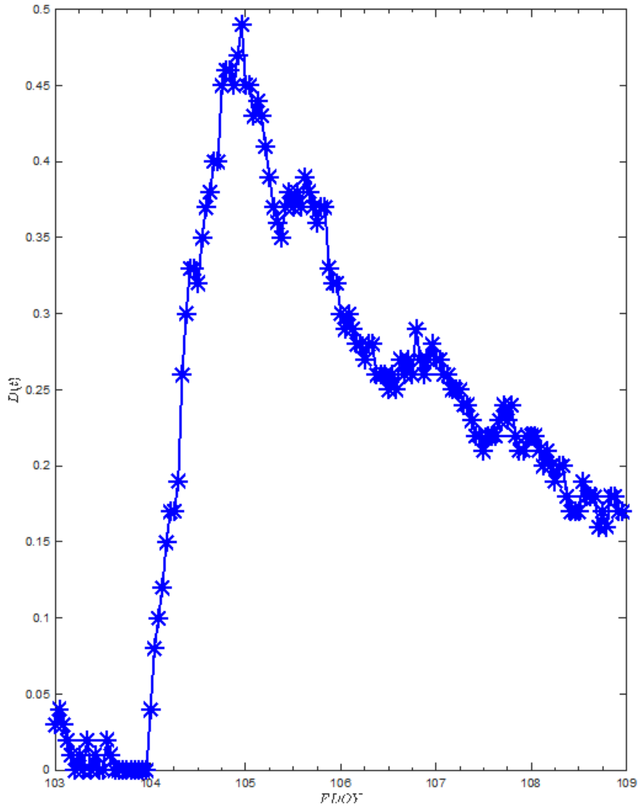

Figure 2 (a): Forbush Decrease magnitude (D) for the April 13, 2013 event.

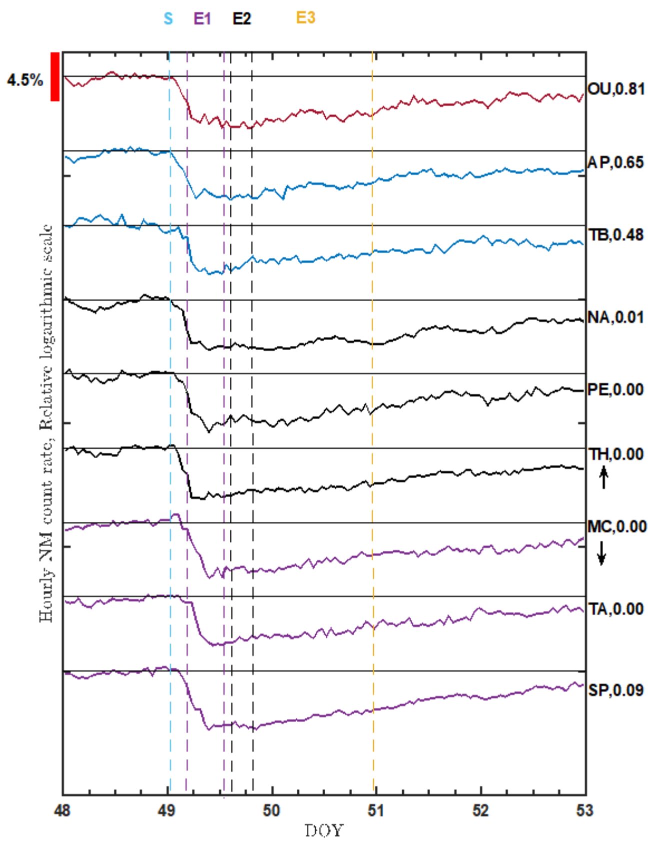

Figure 1 (b): Hourly Count rates for selected NM stations before and during the Forbush decrease

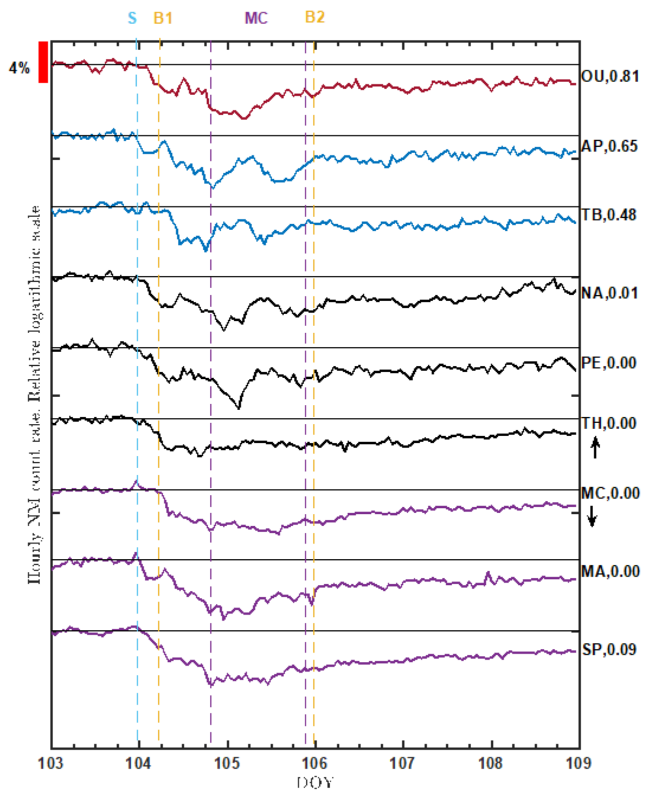

Figure 2 (b): Hourly Count rates for selected NM stations before and during the Forbush decrease event for the April 13, 2013 event.

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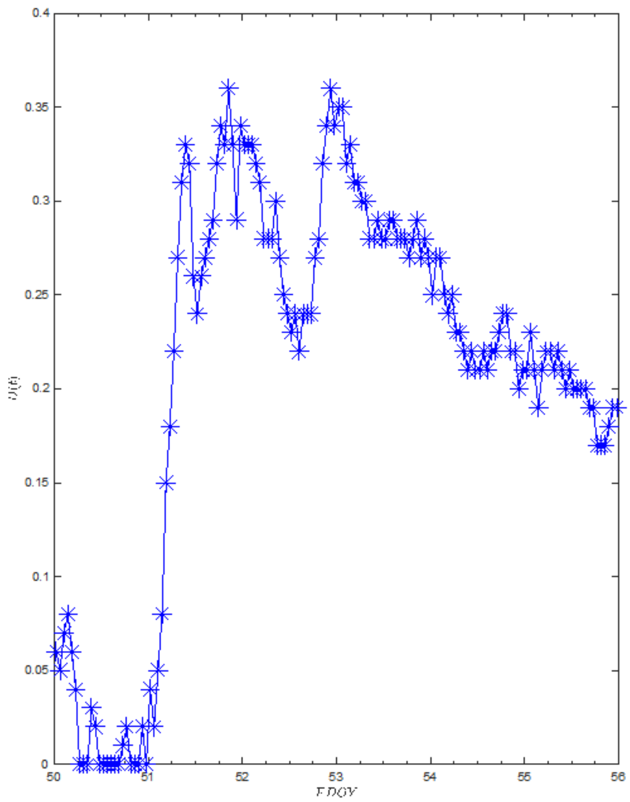

Figure 3 (a): Forbush Decrease magnitude (D) for the February 2014 event.

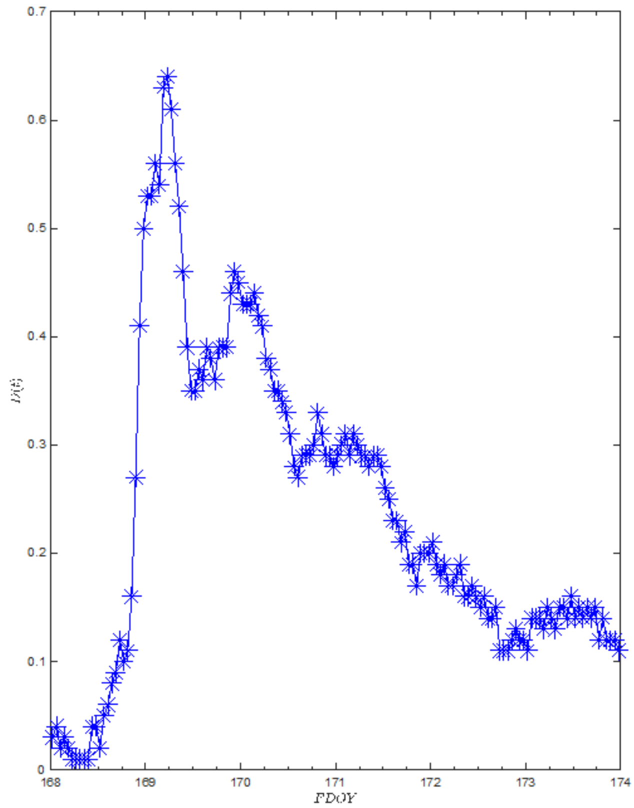

Figure 4 (a): Forbush Decrease magnitude (D) for the June 2012 event.

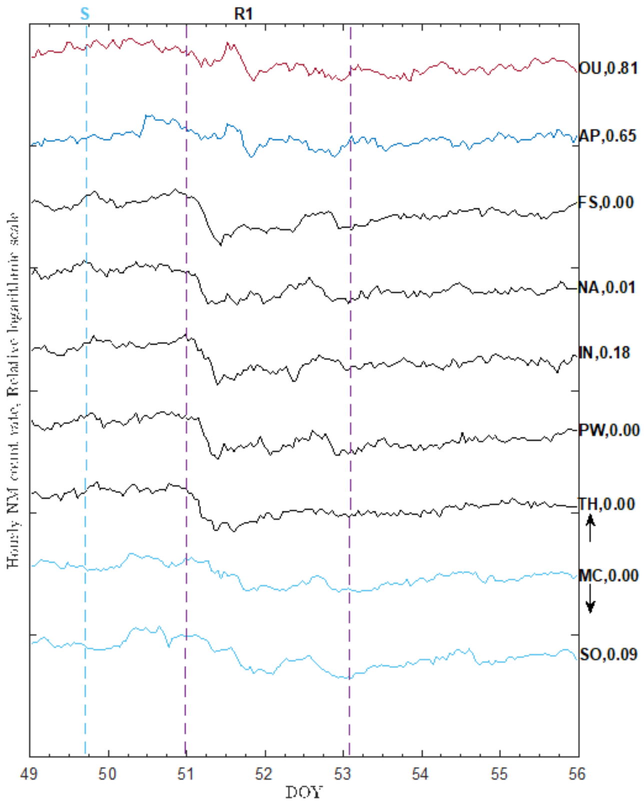

Figure 3 (b): Hourly Count rates for selected NM stations before and during the Forbush decrease event for the February 2014 event

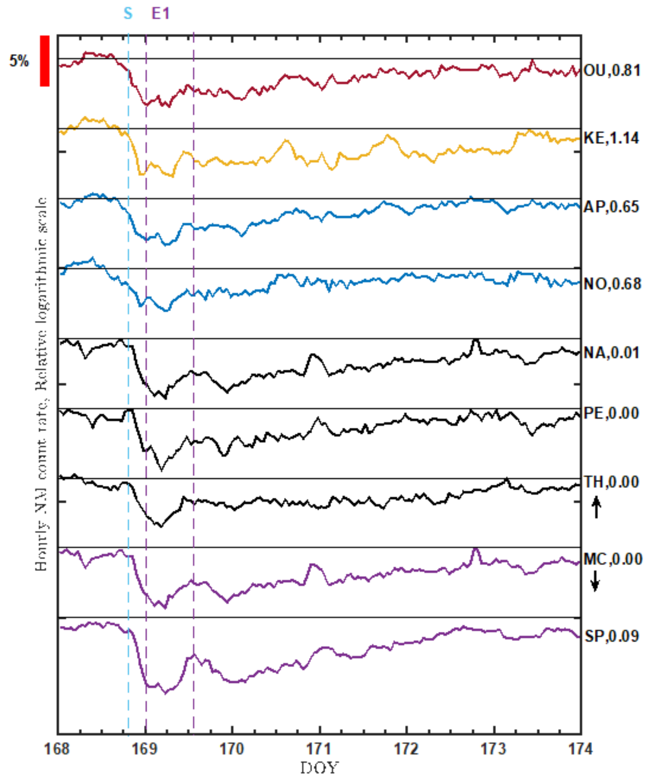

Figure 4 (b): Hourly Count rates for selected NM stations before and during the Forbush decrease event for the June 2012 event

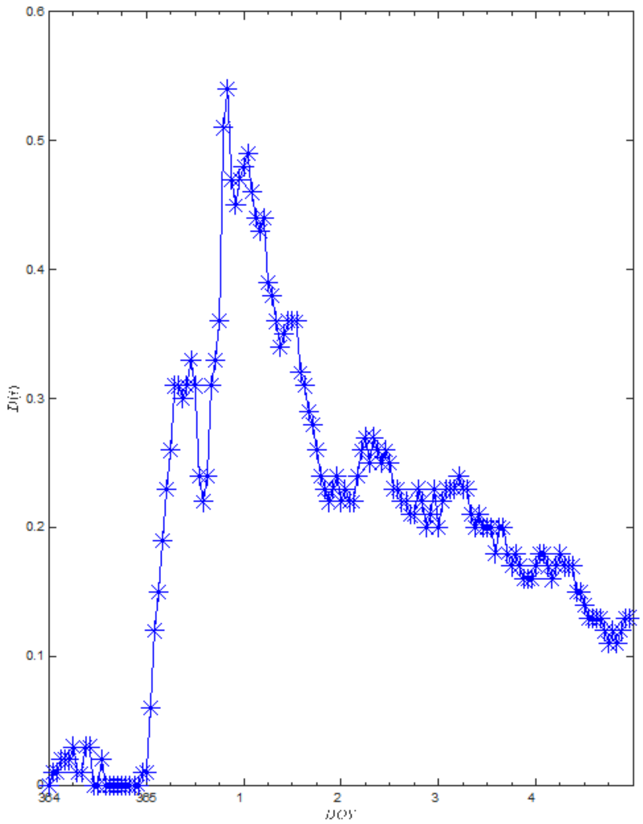

Figure 5 (a): Forbush Decrease magnitude (D) for the December 2015 event.

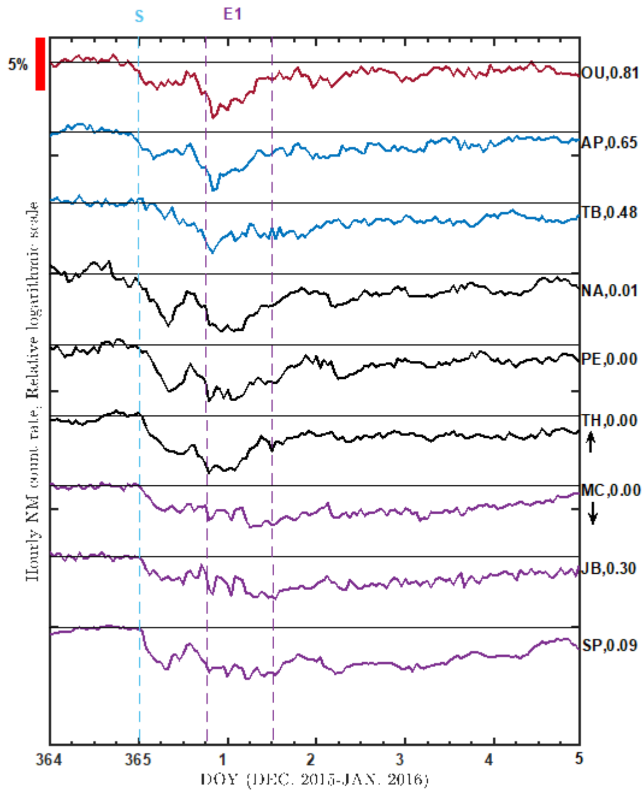

Figure 5 (b): Hourly Count rates for selected NM stations before and during the Forbush decrease event for the December, 2015 event

4. Discussion

Forbush decreases are temporary/short term variations in the flux of galactic cosmic rays caused by ICMEs [7, 8]. These ICMEs are usually associated with strong magnetic structures in the solar wind. This type of decrease is usually followed by a gradual recovery lasting between 5 - 7 days. [6, 8, 11]. They are classified into three basic types; one type caused by a shock and ejecta, a second type caused by a shock only and a third type caused by an ejecta only [8, 11].

In order to understand which type has more influence on the flux of GCR, we analysed count rate of GCRs data available in the catalog of worldwide network of NMs; figure 1 b to 5b and modelled the magnitude of decrease (D) for five candidate events.

For the Feb 2011 event (figure 1a), we see that the magnitude (D (t)) of the Forbush decrease is highest on Day of the Year (DOY) 49 corresponding to sharp decrease in the flux of GCR on day 49 last for about 5 days followed by a gradual recovery. This can be attributed to the passage of an ICME which arrived earth on 18th February, 2011 [12]. The passage of an ICME can cause temporary decreases in the flux of GCRs [8, 11]. The flux is seen to show a sharp decrease immediately the shock arrived (S) suggesting that this type of decrease is caused by the arrival of a shock only [8].

Similarly, Hourly count rates of GCRs exhibit similar sharp decreases starting on DOY 104 with temporary variations between DOY 104 to DOY 106 with a maximum decrease of highest magnitude (2a) on DOY 105. The temporary variations observed during the period of Forbush decrease is due to the passage of a magnetic cloud associated with a magnetic flux rope [6, 13].

For the February 2014 event, the Forbush decrease occurs on DOY 51 corresponding to the ICME of 8 February 2014. This suggests that the changes in the flux are due to arrival of a shock associated with the ICME [8, 14 - 16]. The observed sharp decrease in flux on DOY 52 suggests a second decrease in flux, which can be attributed to the shock and ejecta type [11]. Thus; a shock and ejecta type of Forbush decrease is observed [8, 11]. The Forbush decrease has its highest magnitude on DOY 52 (see figure 3a).

Figure (4b) shows a decrease of 5% in the flux of GCRs corresponding to the arrival of a shock (S) on DOY 168.5. The maximum decrease is observed on DOY 169 (see magnitude of decrease in figure (4a)). This suggests that the arrival of a shock associated with a ICMEs can cause temporary decrease or variations in the flux GCRs (14 - 16).

Likewise, a decrease of 5% is observed in the flux of GCRs across all the NMs on DOY 365, lasting for about 5 days with its highest magnitude on DOY 1. This also corresponds to the arrival of a shock S (see figure 5b) associated with the ICME of December, 2015 [17].

Interestingly, our results revealed that the magnitudes of Forbush decrease D (t) can be used to detect the arrival of an ICME and to explain the characteristics of Forbush decrease.

Secondly, we observed that Forbush decrease caused by shock and or ejecta due to the arrival of an ICME are detected by all polar NMs at the same time. The time of arrival at earth and magnitude of decrease may depend on the viewing direction of the station.

5. Summary

The short - term variation of galactic cosmic ray flux caused by interplanetary coronal mass ejections (ICMEs) and their associated shocks or magnetic flux rope is known as Forbush decrease. This temporary decrease in the flux of galactic cosmic rays is observed at earth by NMs at locations that were possibly passed by the ICME depending on the stations viewing direction. Here, we modelled the magnitude of Forbush decrease for 5 candidate events and compared results with available Forbush decreases observed at earth by different neutron monitors. We find that the magnitudes of Forbush decrease D (t) can be used to detect the arrival of an ICME and to explain the characteristics of Forbush decreases. Secondly, we observed that Forbush decrease caused by shock and or ejecta due to the arrival of an ICME are detected by all polar NMs at the same time and also showed similar characteristics excepts for the distinct differences in recovery times. The time of arrival at earth and magnitude of decrease may depend on the viewing direction of the station.

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