# Rigidity Dependence of Forbush Decreases

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**Abstract:** For the study of the propagation and modulations of cosmic rays, it is important to know the mechanism of interactions between primary cosmic rays and the ambient magnetized plasma. As the one of the typical events of such interactions, we choose the Forbush decrease in this investigation. To get a clue to figure out the mechanism, as the first trial, we have analyzed the relationships between the extent of the dips of cosmic-ray intensity at Forbush decreases and the rigidity of corresponding primary cosmic rays. For this analysis, we have used not only the data of a worldwide network of neutron monitors, but also the data obtained using the large area multidirectional muon telescope of GRAPES-3 at Ooty, India.

**Keywords:** Forbush decrease, rigidity dependence, Solar flare, propagation and modulations.

## 1 Introduction

For the study of the propagation and modulations of galactic cosmic rays through the Helio magnetosphere, it is important to know the mechanism of interactions between primary cosmic rays and the ambient magnetized plasma.

Forbush decrease is the one of the typical phenomenon of such interactions that the observed intensity of cosmic rays decreases temporary during magnetic storms. After passing by the interplanetary shock wave caused by a solar flare and/or the subsequent Coronal Mass Ejection, the region where cosmic rays are difficult to penetrate is formed behind them. In the region, the density of galactic cosmic rays decreases by more than a few to 10 % at several GV. It is called Forbush decrease that the intensity decrease observed at the earth passing through this region. As large Forbush decreases, 10 to 25 % of decreases have been observed by the neutron monitor.

Consulting the review of Cane (2000) [1] and following the preceding studies [2] [3], we decided to analyze the relationships between the extent of the dips of cosmic-ray intensity at Forbush decreases and the rigidity of corresponding primary cosmic rays, as the first trial, to get a clue to figure out the mechanism of interactions between primary cosmic rays and the ambient magnetized plasma.

## 2 Rigidity dependence of Forbush decrease

### 2.1 Observational sites and median rigidities

For this analysis, we have used not only the data of a worldwide network of neutron monitors (NM), but also the data obtained using the large area multidirectional muon telescope of GRAPES-3 at Ooty, India. The list of those 17 NM stations and corresponding median primary rigidities ($R_{\mathrm{m}} = 10.0 \sim 31.6\,\mathrm{GV}$) calculated from the tables given by Yasue *et al*. (1892) [4] is shown below (Table.1).

| NM station | $R_{\mathrm{m}}$ (GV) |
|---|---|
| Alma-Ata | 15.8 |
| Apatity | 12.6 |
| Athens | 25.1 |
| Beijing | 25.1 |
| Haleakala | 31.6 |
| Inuvik | 12.6 |
| Keil | 15.8 |
| Lomnicky Stit | 12.6 |
| McMurdo | 12.6 |
| Mexico | 25.1 |
| Moscow | 15.8 |
| Novosibirsk | 15.8 |
| Potchefstroom | 20.0 |
| SouthPole | 10.0 |
| Tbilisi | 20.0 |
| Thule | 12.6 |
| Yakutsk | 12.6 |

**Table 1**: List of NM stations and corresponding median primary rigidities ($R_{\mathrm{m}}$ in GV).

For the multidirectional muon telescope of GRAPES-3, the list of 9 directional components and corresponding median primary rigidities ($R_{\mathrm{m}} = 64.4 \sim 92.0\,\mathrm{GV}$) calculated by Nonaka (2006) [5] is shown as Table.2.

| Direction | $R_m$ (GV) |
|---|---|
| NW | 73.2 |
| N | 73.5 |
| NE | 92.0 |
| W | 64.4 |
| V | 66.3 |
| E | 82.9 |
| SW | 70.0 |
| S | 69.9 |
| SE | 88.7 |

**Table 2**: List of directional components and corresponding median primary rigidities ($R_m$ in GV).

### 2.2 Forbush decrease events

For the present analysis, from the daily averaged data observed by the stations described above [6] during the period from February 2000 to October 2011, Forbush decrease events are selected by the following conditions:

(1) A candidate of the event is accompanied by a large solar flare on the list of Space Weather Prediction Center of NOAA [7]

(2) For the data of McMurdo station, the event showes more than 3 % decrease when comparing the average counting rate of three preceding days

28 Forbush decrease events thus selected are listed in Table.3. In the table, sites of the corresponding solar flare are also listed (9 occurred on the East side and 17 on the West side). Among them, 26 Forbush decrease events are accompanied by the solar flares with the X-ray intensity of M and X classes.

| Date | Site | X-ray (W/m$^2$) |
|---|---|---|
| 2000.02.12 | E | 1.3E-05 |
| 2000.06.09 | W | 2.3E-04 |
| 2000.11.27 | W | 4.0E-04 |
| 2001.04.09 | E | 8.4E-05 |
| 2001.04.12 | W | 2.3E-04 |
| 2001.08.28 | E | 5.3E-04 |
| 2001.09.26 | E | 2.6E-04 |
| 2001.10.22 | W | 1.6E-04 |
| 2001.11.07 | W | 1.0E-04 |
| 2001.11.25 | W | 9.9E-05 |
| 2001.12.31 | - | - |
| 2002.01.01 | - | - |
| 2003.05.30 | W | 1.3E-04 |
| 2003.10.22 | E | 5.4E-04 |
| 2003.10.30 | W | 1.7E-03 |
| 2004.11.08 | W | 2.0E-04 |
| 2005.01.03 | E | 1.7E-04 |
| 2005.01.19 | W | 3.8E-04 |
| 2005.07.17 | W | 1.2E-04 |
| 2005.08.25 | W | 5.6E-05 |
| 2005.09.11 | E | 1.7E-03 |
| 2006.12.08 | E | 9.0E-04 |
| 2006.12.15 | W | 3.4E-04 |
| 2011.02.18 | W | 2.2E-04 |
| 2011.02.19 | W | 2.2E-04 |
| 2011.09.11 | W | 2.1E-04 |
| 2011.09.27 | E | 1.9E-04 |
| 2011.10.06 | W | 3.9E-05 |

**Table 3**: List of Forbush Decreases selected.

## 3 Results and Discussion

For every selected event in Table.3, a scatter plot is drawn taking the median primary rigidity in the abscissa axis and the extent of the dip of cosmic ray intensity in the axis of ordinate.

Almost all the scatter plots show very clear median primary rigidity dependence of the dip of a Forbush decrease. And when they are plotted in log-log scale, almost all the events show a broken line spectrum as shown in Fig.1, that consists of two lines corresponds to the lower rigidities and to the higher ones. This means the data from the muon telescope show the steeper spectrum than those from NM stations. If we calculate the slope (or the power index) for each line, they show a common tendency of softening.

### 3.1 Average for the all events

Fig.1 shows the average median primary rigidity dependence of the dip of all 28 Forbush decreases.

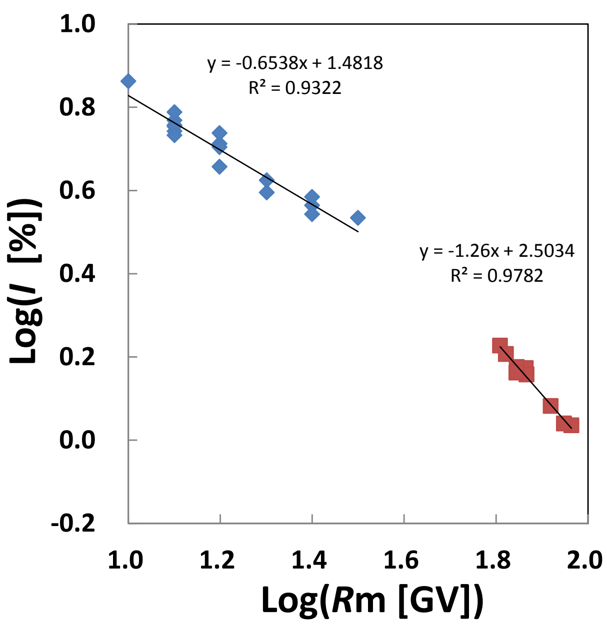


**Fig. 1**: Median rigidity ($R_m$ in GV) dependence of average extent ($I$ in %) of the dips for all 28 Forbush decreases

From this average plot (Fig.1), the power indices correspond to each rigidity region are obtained as $-0.65\pm0.05$ for the NM stations and as $-1.26\pm0.08$ for the muon telescope.

### 3.2 Flare site correspondence

Besides the average feature described in the previous subsection, all the scatter plots indicate some tendency by flare to flare associated with. That is the flare site effect on the slopes of the rigidity dependence investigated here.

Fig.2 shows the average median primary rigidity dependence of the dip of 9 Forbush decreases associated with the solar flare on the East side.

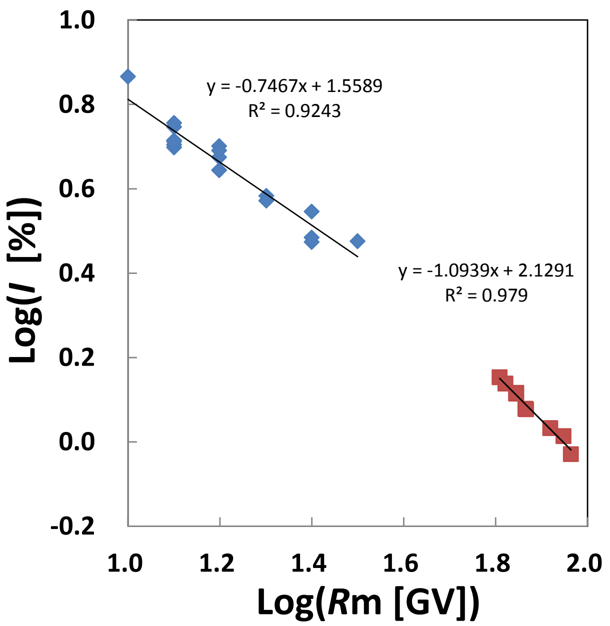


**Fig. 2**: Median rigidity ($R_m$ in GV) dependence of average extent ($I$ in %) of the dips for 9 Forbush decreases associated with the solar flare on the East side

From this average plot (Fig.2), the power indices correspond to each rigidity region are obtained as −0.75±0.06 for the NM stations and as −1.09±0.07 for the muon telescope.

Fig.3 shows the average median primary rigidity dependence of the dip of all 17 Forbush decreases associated with the solar flare on the West side.

From this average plot (Fig.3), the power indices correspond to each rigidity region are obtained as −0.63±0.05 for the NM stations and as −1.38±0.15 for the muon telescope.

Power indices obtained from these three figures are summarized in Table.4. The corresponding values of determination coefficient ($R^2$, square of a correlation coefficient) are indicated in the each figure.

| $R_m$ in GV<br>Site | NM stations<br>(10.0∼31.6) | muon telescope<br>(64.4∼92.0) |
|---|---|---|
| All | −0.65±0.05 | −1.26±0.08 |
| East | −0.75±0.06 | −1.09±0.07 |
| West | −0.63±0.05 | −1.38±0.15 |

**Table 4**: Power indices.

Distributions of the power indecies are also shown in Fig.4 and Fig.fig:muon, for the NM stations and the muon telescope, respectivery.

From the Table.4 and the distributions (Fig.4 and 5), power indices for the lower rigidities (NM) become duller

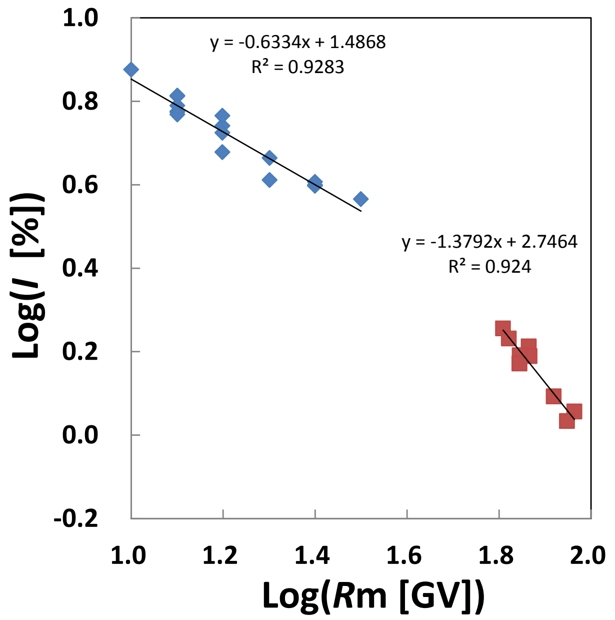


**Fig. 3**: Median rigidity ($R_m$ in GV) dependence of average extent ($I$ in %) of the dips for 17 Forbush decreases associated with the solar flare on the West side

from East to West and power indices for the higher rigidities (muon) steeper from East to West, in an opposite manner.

Though the reason is not clear at this time, we speculate that the difference possibly reflects the spatial distribution of the diffusion coefficient (or scattering mean free path) of galactic cosmic rays around the magnetically disturbed region (i.e. the cause for the Forbush decrease) and/or this might be a hint to theoretical approaches, e.g. Nishida (1983) [8]. The pictures representing our speculation are indicated in Fig.6 and Fig.7, corresponding to East and West side flare, respectively. For more precise analyses, we must take into account the effect of detector response to the primary cosmic rays as Sakakibara et al. (1984) [3].

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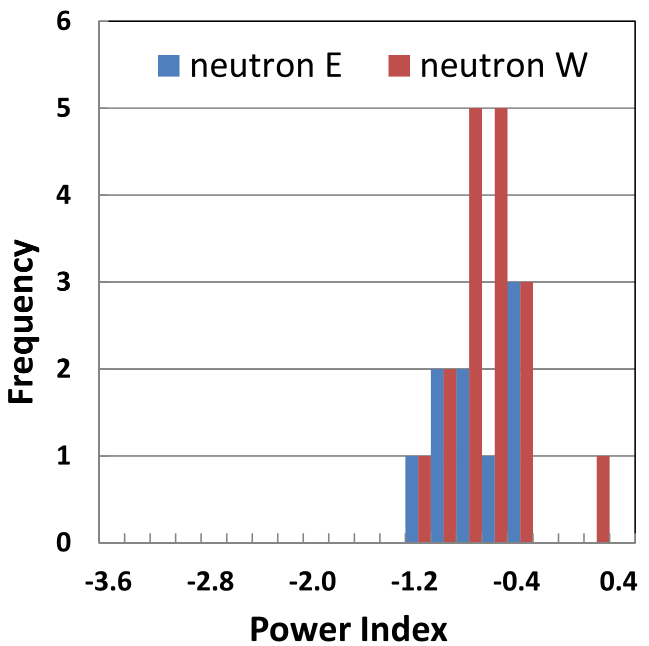


**Fig. 4**: Power index distribution for the data of the NM stations

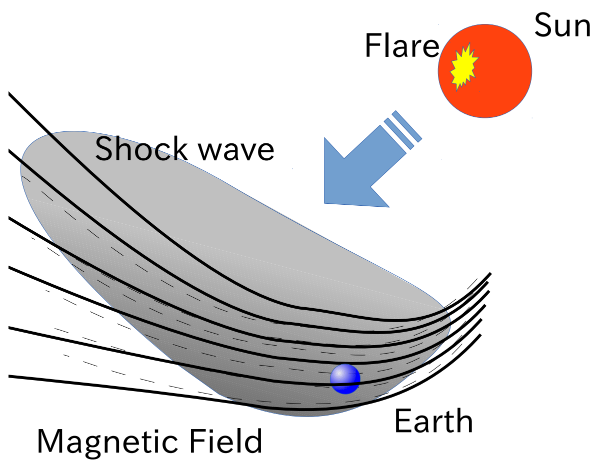


**Fig. 6**: In case of East side flare, the interplanetary magnetic field near the earth might be more compressed by the shock wave.

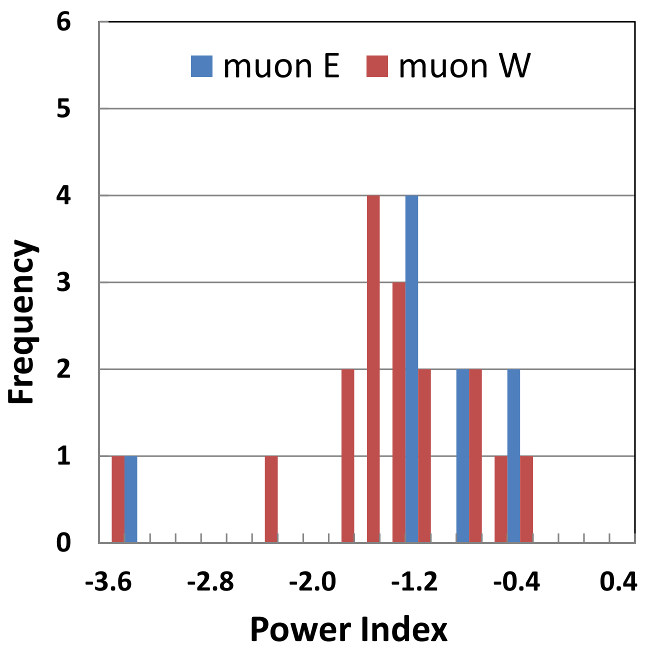


**Fig. 5**: Power index distribution for the data of the muon telescope

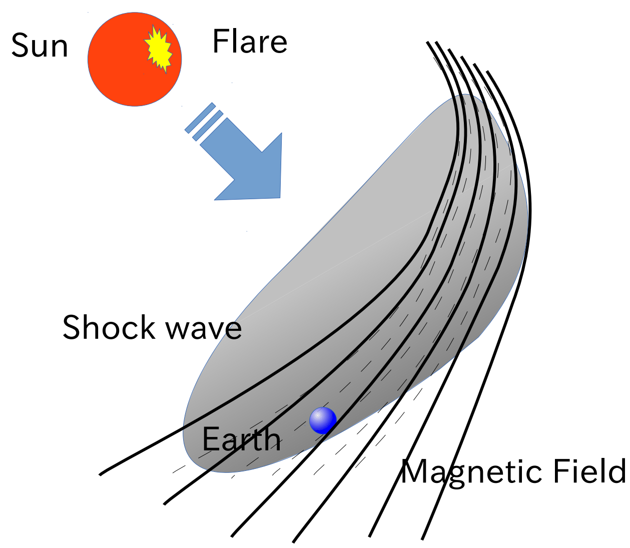


**Fig. 7**: In case of Wast side flare, the interplanetary magnetic field near the earth might be less compressed by the shock wave.