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# Rigidity Dependence of Galactic Cosmic Ray Modulation: 2. Forbush decreases

H.S. Ahluwalia , M.M. Fikani and R.C. Ygbuhay
*Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM 87131, USA*
Presenter: H.S. Ahluwalia (hsa@unm.edu), usa-ahluwalia-HS-abs2-sh34-poster

Modulations of the galactic cosmic ray (GCR) intensity, on all time scales, contain a wealth of information regarding their mode of transport in the heliosphere. One way to extract crucial information from the data is to study the rigidity dependence of modulation effects. We do this using data obtained with a variety of detectors on ground, at mountain altitudes and on balloons, satellites and space probes. For such studies to be meaningful, it is important to have a clear understanding of the response of the detectors used. There is a great deal of confusion on this topic in papers published in refereed journals. For example, the median rigidity of response (Rm) to GCR spectrum, for Mt. Washington neutron monitor is given as ranging from 5.4 GV to 14 GV, by the same authors, at different times. We define Rm as GCR rigidity below which lies 50 % of the detector counting rate. It is easily calculated from the latitude survey data, obtained at sea level and higher altitudes. We list computed Rm values for some observing sites of the global network and use them to plot the rigidity dependence of Forbush decreases over a broad range of GCR spectrum; we use data from underground muon telescopes for this purpose.

## 1. Introduction

A phenomenological understanding of the galactic cosmic ray (GCR) intensity modulation, over a range of time scales and rigidities (R), has been arrived at based on analyses of data from the global network of ion chambers (ICs), underground (muon) telescopes, and neutron monitors (NMs) over the last seven decades; NM network has operated stably for more than half a century. These data contain a wealth of information pertaining to parameters of GCR transport in the turbulent interplanetary magnetic field (B). Recently, we argued that a large part of 11-year modulation may be accounted for in terms of convection and diffusion processes in the solar wind (speed = V); convection is initiated by the solar wind electric field **E** (= **V x B**) which drives an electric drift (**E x B**) for charged particles away from the sun, setting up a radial density gradient in the heliosphere [1]; GCRs from the local interstellar medium diffuse inward to minimize the gradient. The inward flow nearly cancels the outward flow; a small imbalance between them leads to a diurnal variation observed by detectors situated on the spinning earth [2]. Convection is a local effect, depending upon the value of **B** and **V** at the point of observation in the heliosphere; thereby it controls the onset phase of modulation, often leading to Stoker- Carmichael steps in the descending phase of a cycle at earth's orbit [3] and in outer heliosphere [4]. At higher GCR rigidities ($R > 10$ GV) the neutral current sheet drifts (outward for $A > 0$ and inward for $A < 0$) play a secondary role, such as shifting the diurnal anisotropy phase from east-west to radial direction (sunward) during solar minima in $A > 0$ epochs. Also, charged particle drifts contribute little to the latitudinal gradients at high and low rigidities near solar maxima [5, 6]. It is clear now that charged particle drifts contribute very little to the observed modulations both at high [7, 8] and low GCR rigidities [9].

The rigidity dependence of modulation arises from the local as well as global GCR contributions. To explore this dependence, one uses data obtained with a variety of detectors located underground, at sea level, at mountain sites, as well as on balloons, satellites, and space probes. For these studies to be meaningful, it is important to have a clear understanding of the response characteristics of the detectors involved. We characterize the detectors in terms of their median rigidity of response (Rm) to GCR spectrum; below it is 50 % of detector counting rate [10]. It is easily computed from the detector response function, derived from the latitude survey data at sea level and mountain altitudes. Data for NMs are available from several surveys undertaken by different research groups over several decades. Most of them are carried out near solar minima for an understandable reason that these epochs are free of transients (solar cosmic rays, Forbush decreases, etc); also the intensity of lowest rigidity GCRs is largest then. Some colleagues define effective rigidity of modulation for NMs in an ad hoc manner [11]. The scope of this paper is limited; we illustrate the usefulness of our Rm values (see Table 2 of Paper 1) by applying them to study the rigidity dependence of two large Forbush decreases.

## 2. Response Functions

Neutron monitor response functions are provided in [12, 13, 14, 15, 16]. We have used the differential response curves of [13] and [14] to compute Rm values for several NM sites [17]. We include Rm = 67 GV for IC at Yakutsk computed by Fujimoto et al. [18]; their definition of Rm is the same as ours, IC data are from Ahluwalia [19]. Rm values for underground muon telescopes have been derived by Fujimoto et. al [18],utilizing the theoretical calculations of Murakami et. al [20] who obtained response functions for muons by solving numerically the equations of hadronic cascades in the atmosphere, by assuming Feynman scaling for hadronic interactions for GCR spectrum incident at the top of the atmosphere. Here, we use Rm values to study two large Forbush decreases (FDs), spanning a broad range of GCR rigidity spectrum.

## 3. Computed Rm Values

We illustrated the usefulness of our Rm values (see Table 2 of Paper 1), over a range (1 to 70 GV) of detector response, by applying them to plot 11-year modulation amplitudes for two adjacent solar cycles (21, 22) using data given in [11]. Here, we further test the usefulness of our Rm values over a broader range, from IMP to underground detectors (1 to 300 GV). We plot amplitudes for two very large Forbush decreases observed during the recovery phase of cycles 20 (August 1972) and 21 (July 1982). The results are preliminary; details will be reported elsewhere.

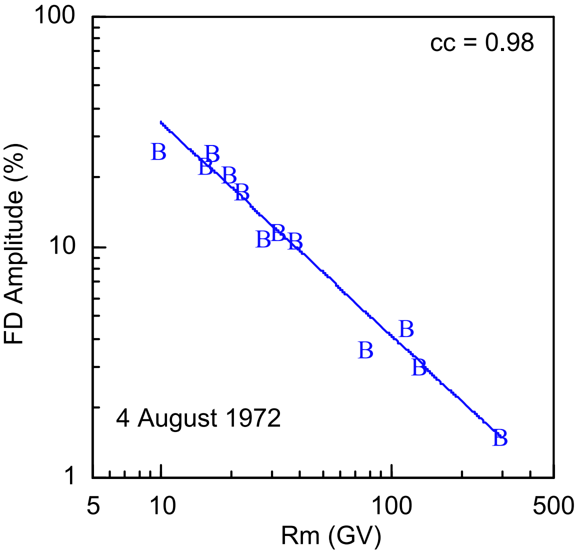

**Figure 1.**

## 4. Forbush Decreases

We consider two large Forbush decreases (FDs) for a study of the rigidity dependence of their amplitudes recorded by the global network of detectors, including underground telescopes (UTs). One FD occurred in August 1972 and the other in July 1982. The first event occurred during solar cycle 20 for A > 0 epoch while the latter happened during the declining phase of cycle 21 for A < 0 epoch. The data and detailed solar-terrestrial relationships for both events have been reported at length in literature.

### 4.1. Forbush decrease of August 1972

Sunspot activity was responsible for a remarkable series of happenings on the sun and in the heliosphere for the month of August 1972. Pomerantz and Duggal [21] report on the 'record breaking' Forbush decrease on 4 August 1972 which reduced GCR intensity at the South Pole by 35 %, at which time solar wind speed (measured by Pioneer 9 at 0.78 a.u.) jumped to about 1200 km/s [22]. The magnetic field configuration of the accompanying shock (ICME) produced a flux decrease in muon detectors deep underground [23]; FD was also recorded by IC at Yakutsk [24] and by the multidirectional muon telescopes at Nagoya [25]. Agrawal et. al [26] reported on FD recorded by the global network of NMs and the surface muon telescopes. They also compiled detailed information on the solar-terrestrial relationships of the events during the month of August 1972. Therefore, a comprehensive data set is available to us for a study the rigidity dependence of this FD. Figure 1 shows a log-log plot of FD amplitudes (from the papers cited above) and Rm values computed by us and by Fujimoto et. al [18]. The line represents a power law fit to the data; an inverse dependence on GCR rigidity is seen clearly. Agrawal et. al [26] give the exponent of the rigidity as - 1. 2 ± 0. 2 for NM data, whereas Sekido et. al [25] give an exponent of - 0. 75. Our rigidity exponent of - 0. 93 lies between the two values.

### 4.2. Forbush decrease of July 1982

Fillius and Axford [27] note that Forbush decrease of 14 July 1982 reduced GCR intensity to the lowest level for cycle 21, three years away from sunspot maximum, well past the epoch of solar polar field reversal in 1980 [28]; see also Fig. 7 in [29]. Cliver et. al, [30] discuss the solar-terrestrial relations and heliospheric implications of this event, in considerable detail. Lockwood and Webber [31] studied its rigidity dependence using data from IMP and NMs. The Rm values used by them are under-estimated, as discussed above (see their Table 1, p. 5449). Fortunately, data are also available for this FD from UTs at Embudo and Socorro [32]. So, the rigidity range for our plot can be extended to 300 GV. Figure 2. depicts a log-log plot of FD amplitudes (from the papers cited above) and Rm values computed by us and by Fujimoto et. al [18]. The diagonal line represents a power law fit to the data from 1 GV to 300 GV (cc = 0.98). Again, an inverse dependence of FD amplitude on GCR rigidity is seen very clearly. Fenton et. al [33] give the exponent of the rigidity as - 0.8, using data obtained with the Australian network of four NMs over a limited rigidity range. Our value of - 0.61 over a larger rigidity range, is flatterer. A detailed study of these FDs is in progress. Results will be reported elsewhere.

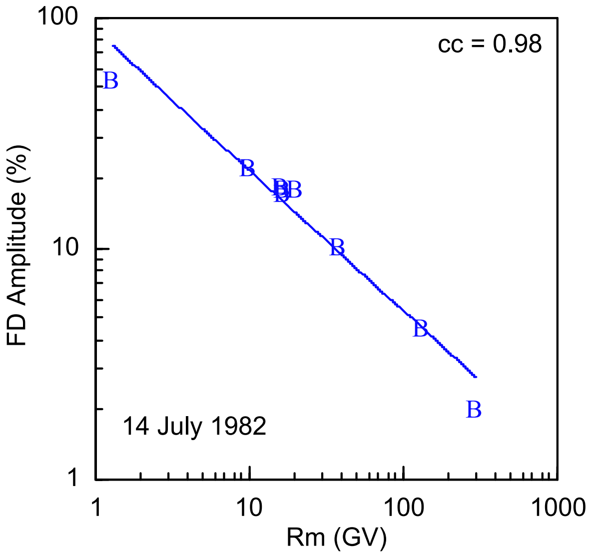

**Figure 2.**

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