

# Hourly Measurements of Cosmic-ray Spectral Variation during Forbush Decreases using Ground-based Neutron and Muon detectors

W. Mitthumsiri,<sup>a,\*</sup> D. Ruffolo,<sup>a</sup> K. Munakata,<sup>b</sup> P. Muangha,<sup>a,c</sup> A. Sáiz,<sup>a</sup> P. Evenson,<sup>d</sup> P.-S. Mangeard,<sup>d</sup> W. Nuntiyakul<sup>e</sup> and the Global Muon Detector Network Collaboration

<sup>a</sup>Department of Physics, Faculty of Science, Mahidol University, Bangkok, Thailand

<sup>b</sup>Department of Physics, Shinshu University, Matsumoto, Nagano, Japan

<sup>c</sup>National Astronomical Research Institute of Thailand (NARIT), Chiang Mai, Thailand

<sup>d</sup>Bartol Research Institute, Department of Physics and Astronomy, University of Delaware, Newark, DE, USA

<sup>e</sup>Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, Chiang Mai, Thailand

E-mail: [warit.mit@mahidol.edu](mailto:warit.mit@mahidol.edu), [ruffolo.physics@gmail.com](mailto:ruffolo.physics@gmail.com), [kmuna00@shinshu-u.ac.jp](mailto:kmuna00@shinshu-u.ac.jp)

Solar storms can disturb Galactic cosmic-ray (GCR) fluxes within the heliosphere at short time scales in events known as Forbush decreases (FDs). We extract hourly GCR spectral variations during FDs from a global network of ground-based neutron monitors and muon detectors using two independent methods: A) fitting a GCR rigidity spectral model with anisotropy up to second order, and B) analyzing time delay distributions between successive neutron detections by each counter of the South Pole Neutron Monitor to obtain the “leader fraction”. Both methods provide consistent results for spectral index variations during five major FDs between 2015 to 2023 and agree very well with the daily space-based observations by AMS-02 when such data are available. This analysis demonstrates the precision level of ground-based spectral measurements and offers techniques for real-time space weather monitoring (publicly available at <https://neutronm.bartol.udel.edu/realtime/southpole.html>) for use in FD studies and space weather alerts.

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## 1. Introduction

Forbush decreases (FDs) are short-term reductions in the observed intensity of Galactic cosmic rays (GCRs) reaching Earth, followed by a recovery phase lasting from a few hours to several days [1]. They are closely associated with solar activities, particularly interplanetary coronal mass ejections (ICMEs) and high-speed solar wind streams that travel through the interplanetary medium and act as a shield or barrier, partially blocking or deflecting the incoming GCRs. This leads to a sudden drop in cosmic ray intensity measured by ground-based neutron monitors (NMs) and muon detectors (MDs) or space-based detectors. The extent and spectral feature of the decrease depends on the characteristics of the solar disturbance, as well as the position of the Earth relative to the ICME's path [2].

Studying the GCR spectral variation during an FD using a network of NMs at different geomagnetic locations is challenging because of cross-calibrations, local weather effects, and the enhanced anisotropy. However, the improvement in electronics in the last decade has allowed a single NM station to measure the GCR spectral index ( $\Gamma$ ) at various time scales. Here,  $\Gamma$  is defined as  $F \propto P^{-\Gamma}$  where  $F$  is GCR flux and  $P$  is the rigidity (momentum per charge of a particle). Upgraded NMs are capable of recording the time-delay distribution of two successively detected neutron events. From the distribution, we extract the “leader fraction,” [3] which can be calibrated to yield the value of  $\Gamma$ .

Another technique called the global analysis fit (GFA) has been developed using the combined data from a global network of NMs and MDs [4]. NMs are omnidirectional detectors for primary cosmic rays with median rigidity of approximately 10 – 35 GeV depending on their geomagnetic rigidity cutoff locations, while MDs have multiple directional channels covering higher median rigidity ranges of roughly 50 – 100 GV. The GFA combines data from several NMs and 4 MDs located in Japan, Kuwait, Australia, and Brazil and performs simultaneous fitting of both NM and MD data sets by separating the temporal and anisotropic components of the spectrum, resulting in an accurate global GCR spectral model at wide rigidity range.

In space, AMS-02 experiment onboard the International Space Station has measured the daily spectrum of GCR protons, which contribute to  $\approx 90\%$  of all types of particles (except for the neutrinos), during 2011 – 2019 [5]. The GCR spectral variations during some FDs have been analyzed by [6]. Despite many advantages of being direct observations, AMS-02 results are directionally averaged, retrospectively available, and at daily time scale. Therefore, our hourly ground-based measurements which could be made publicly accessible in real time are valuable complementary to the space-based direct observations. In this work, we present our calculated GCR spectral parameters (intensity and  $\Gamma$ ) from the South Pole NM leader fraction and the GFA methods during five major FD events between 2015 and 2023. We then compare our results against those extracted from direct measurements by AMS-02 when data are available.

## 2. Data and Analysis Method

This section is taken mainly from [7], in which more detail of this work is described.

## 2.1 AMS-02 data

We use the daily proton rigidity spectrum measured by AMS-02 from 2011 to 2019 [5]. The proton flux  $\Phi_k$  given in each of 30 rigidity bins is assigned to the geometric mean  $P_k$  of minimum and maximum rigidities of the  $k$ -th rigidity bin, with  $P_k$  values ranging from 1.10 GV to 83.50 GV. We calculate the fractional change in GCR density at  $P_k$  as  $\Delta I_k = (\Phi_k - \Phi_k^0)/\Phi_k^0$ , where  $\Phi_k^0$  is the average of  $\Phi_k$  over a reference interval of the initial three days, before the FD onset. The error of  $\Delta I_k$  is calculated from the total systematic error of  $\Phi_k$  given in the AMS-02 data table. We then estimate the local power-law index  $\Gamma_k$  as the negative slope of a weighted least-squares linear fit to  $\log \Phi_i$  versus  $\log P_i$  for  $i = k - 3, \dots, k + 3$ , i.e., for the 7 data values closest to the  $P_k$  of interest. In this work we estimate  $\Gamma_{10.5}$  for the rigidity  $P_k = 10.5$  GV closest to the South Pole NM median primary rigidity of 11.3 GV.  $\Delta \Gamma_{10.5}$  is then calculated as  $\Gamma_{10.5} - \Gamma_{10.5}^0$  where  $\Gamma_{10.5}^0$  is the average of  $\Gamma_{10.5}$  over the reference interval.

## 2.2 Global Fit Analysis

GFA deduces the best-fit model GCR intensity using 12 independent parameters for each hour that reproduce hourly count rates recorded by NMs and MDs with the minimum chi-squared [4]. In this work, we use 85 hourly count rates recorded by 25 NMs and 60 directional channels of GMDN, all corrected for atmospheric effects and normalized to the average count rate over the reference interval. For each order of anisotropy ( $n = 0, 1, 2$ ), the intensity decrease is modeled as a power law in rigidity and the fit parameters are the power-law index  $\gamma_n$  and anisotropy amplitudes  $\xi_c^{n,m}(t)$  and  $\xi_s^{n,m}(t)$  ( $m = 0, \dots, n$ ) at a reference rigidity  $P_r$ . From the best-fit parameters, the fractional intensity change in space at rigidity  $P$  and time  $t$  relative to the intensity during the reference interval before the FD is given as

$$\Delta I(P, t) = \sum_{n=0}^2 \sum_{m=0}^n P_n^m(\theta) \{ \xi_c^{n,m}(t) \cos m(\phi + \omega t) + \xi_s^{n,m}(t) \sin m(\phi + \omega t) \} (P/P_r)^{\gamma_n(t)}, \quad (1)$$

where  $P_n^m$  is the semi-normalized spherical function,  $\omega = \pi/(12 \text{ h})$ , and  $\theta$  and  $\phi$  are the geographical co-latitude and longitude of the asymptotic direction of GCRs of rigidity  $P$  outside the magnetosphere. For  $P$  close to  $P_r$ , the GCR rigidity spectrum of the reference time interval  $J(P) = J_0(P/P_r)^{-\Gamma(P)}$  is modulated at time  $t$  during the FD to become  $j(P, t) = J(P)[1 + \Delta I(P, t)] = J_0[1 + \Delta I(P_r, t)](P/P_r)^{-[\Gamma(P) + \Delta \Gamma(P, t)]}$ . Using  $\Delta I(P, t)$  from Eq. (1), the change in the spectral index at rigidity  $P_r$  and time  $t$  is given by  $\Delta \Gamma(P_r, t) = -P_r(\partial/\partial P) \log[1 + \Delta I(P, t)]|_{P=P_r}$ . We compare  $\Delta I(P, t)$  and  $\Delta \Gamma(P_r, t)$  with the results extracted from the AMS-02 observations described in the previous section by setting  $P_r = 10.5$  GV using the same reference time interval.

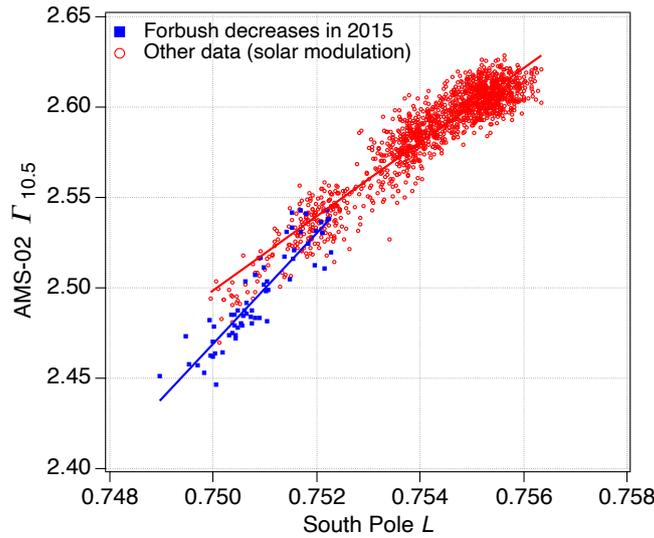
## 2.3 Neutron Monitor Leader Fraction Analysis

The NM leader fraction ( $L$ ) [3, 8] is defined as the fraction of detected neutrons that are “leaders,” i.e., not following other neutrons from the same primary cosmic ray. Using specialized electronics, we record distributions of time delays between two consecutive events detected by the same neutron counter. We use a statistical method to calculate  $L$  for each counter every hour by accumulating the time-delay ( $\tau$ ) distribution which would follow an exponential function ( $n \propto \exp[-\alpha\tau]$ ) for randomly unassociated events (leaders). The measured distribution clearly

deviates from the exponential trend, indicating that some events are temporally associated, i.e., there is a multiplicity of neutron counts from the same cosmic ray shower. The leader fraction  $L$  is defined as

$$L = \frac{\text{Number of pulses in exponential}}{\text{Total number of pulses}}, \quad (2)$$

which represents the inverse multiplicity, and multiplicity relates to primary cosmic ray rigidity, so  $L$  indicates the cosmic ray spectral index. Measurements of  $L$  extend the capability of NMs to observe cosmic-ray spectral variation in addition to monitoring the count rate variation [3, 8, 9]. In this work, we focus on  $L$  from the South Pole NM because it was calibrated vs. the spectral index inferred from AMS-02 daily proton data [10]. Here we compare the South Pole  $L$  (corrected for pressure variation [10]) with the AMS-02 spectral index  $\Gamma_{10.5}$  at 10.5 GV (a value of  $P_k$  close to the South Pole NM median primary rigidity of 11.3 GV) for all times of overlapping data (Figure 1). The correlation between  $L$  and AMS-02  $\Gamma_{10.5}$  is well described by a linear fit with significantly different slopes during the two FDs of 2015 (blue) compared with all other data (red), which characterize solar modulation (i.e., variation with the solar activity cycle) during 2015 – 2019. Here we use the linear fit parameters for the two FD periods in 2015 (blue line) to infer  $\Delta\Gamma$ , the spectral index variation during all five FD events in 2015 – 2023 from the observed  $L$ .

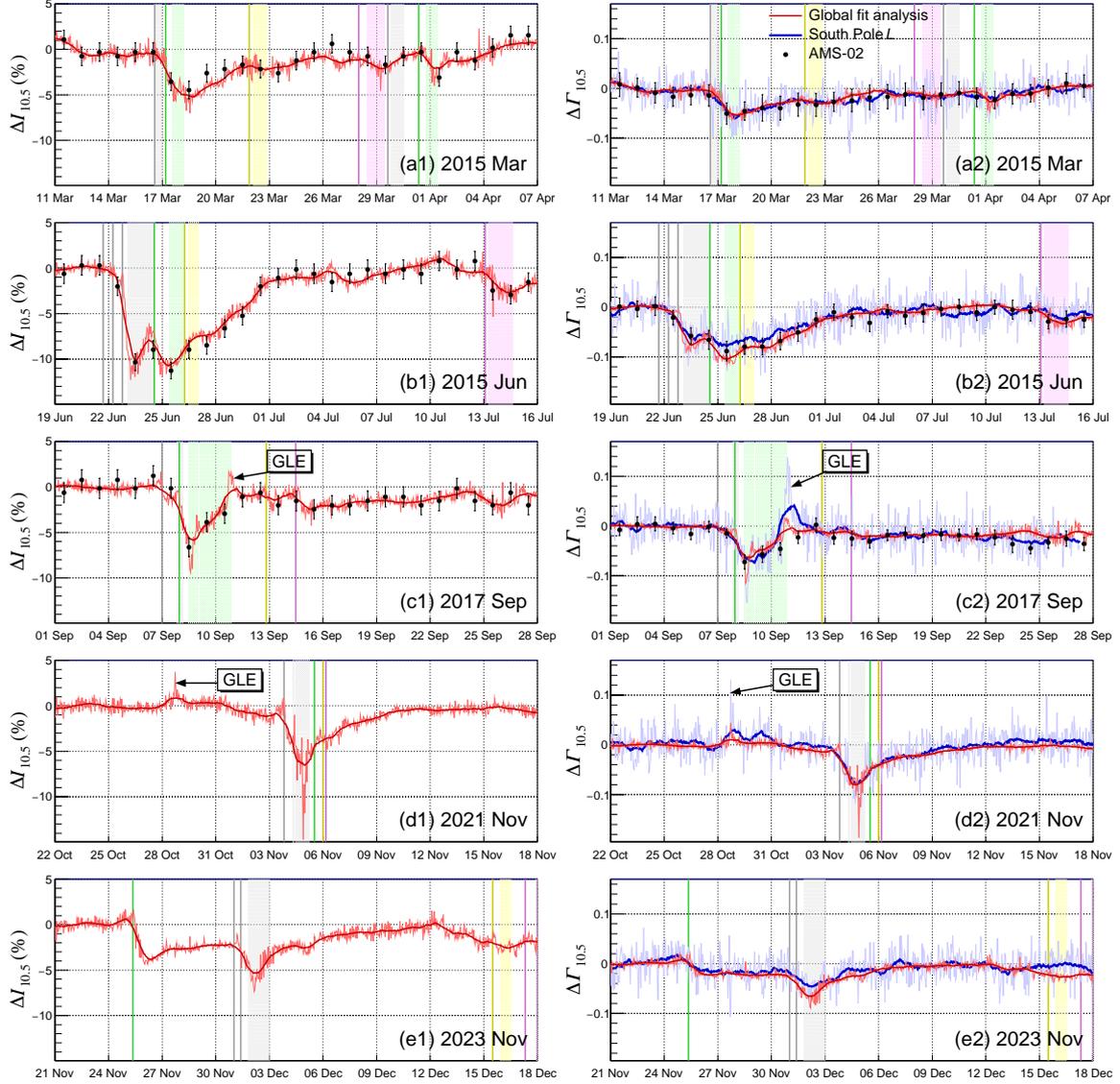


**Figure 1:** Daily South Pole NM leader fraction  $L$  versus AMS-02  $\Gamma_{10.5}$  (cosmic-ray spectral index at 10.5 GV). Blue squares: the two FD periods in 2015. Red circles: all other data during 2015–2019, indicating variation with the solar activity cycle. This figure is from [7].

### 3. Results

We analyze the spectral variation of the GCR during five FD events between 2015 and 2023. Changes in the GCR intensity  $\Delta I(P, t)$  and power-law index  $\Delta\Gamma(P, t)$  at  $P_r = 10.5$  GV over a synodic solar rotation period (27 days) calculated by our methods are shown in Figure 2. Here the changes are relative to the average values of the first three days in each plot (i.e., the reference time

interval). Note that NM data are not shown in the left panels because a single NM does not measure  $\Delta I$  at  $P_r$ ; it responds to a wide range of primary GCR rigidity.



**Figure 2:** Temporal variations of cosmic ray flux  $\Delta I(P, t)$  (left) and spectral index  $\Delta \Gamma(P, t)$  (right) relative to a reference interval (first 3 days of each plot), based on two ground-based observing techniques, GFA (red) and South Pole  $L$  (blue) [hourly data: thin, light curves; 24-hour running averages: thick, dark curves] and, when available, space-based daily AMS-02 proton data (black). Each panel displays values for rigidity 10.5 GV during 27-day solar rotation periods including five FDs starting in (a) 2015 March, (b) 2015 June, (c) 2017 September, (d) 2021 November, and (e) 2023 November. FDs are associated with interplanetary shock arrival at Earth (vertical line) and/or passage of an ICME (shading of the same color). There is very good consistency between all measures of GCR flux and spectral variations. Two GLEs (solar energetic particle enhancements) in (c) 2017 September and (d) 2021 October were observed by ground-based detectors but excluded from published AMS-02 data. This figure is from [7].

## 4. Discussion

This section is taken mainly from [7], which contains more in-depth discussion. The right panels of Figure 2 illustrate the good agreement of  $\Delta\Gamma_{10.5}$  calculated by the GFA and  $L$  methods. Moreover, results from our two methods are consistent with the AMS-02 observations for the first three FD events in 2015 and 2017 when the AMS-02 data are currently available. This demonstrates the reliability and accuracy of ground-based observation of spectral variation. Note also that even the hour-to-hour variation can be examined in the hourly GFA and  $L$  results, while only the daily mean is available from AMS-02. Although the AMS-02 observations can provide the absolute flux measurements, ground-based detectors can monitor GCR spectral variations with better temporal resolution.

This resolution is highlighted by the sharp increases due to ground level enhancements (GLEs) from solar energetic particles on 2017 September 10 and 2021 October 28 in  $\Delta I(P, t)$  and  $\Delta\Gamma(P, t)$  from GFA and South Pole  $L$ . The GLE times were excluded from the published AMS-02 data. When there is a mixture of solar and Galactic particles, which have very different spectra,  $\Delta\Gamma$  is a measure of effective spectral change that serves as an indicator of a GLE. Note also that GLEs have very steep spectra so they more strongly affect the South Pole NM data at lower rigidity.

For each time period in Figure 2, the observed decreases in  $\Delta I$  and  $\Delta\Gamma$  are associated with the arrival of an interplanetary shock (vertical line) followed by its driving ICME (time of passage indicated by shading of the same color) as summarized by Richardson & Cane<sup>1</sup>. Additional shock arrivals listed in the International Service of Geomagnetic Indices<sup>2</sup> are also plotted. However, the event on 2023 November 25 was associated with a shock but no ICME at Earth, and indeed the shock may have partially resulted from a solar wind stream interaction. This is the only event for which we observe almost no change in spectral index,  $\Delta\Gamma$ , indicating a nearly rigidity-independent decrease in cosmic ray intensity. This is consistent with other observations that high-rigidity cosmic rays, with larger gyroradii, can remain unaffected by ICMEs, which are relatively small structures, while interplanetary shocks can have impacts that are nearly rigidity-independent [11].

FD detection can provide alerts for the possible arrivals of interplanetary shocks or ICMEs. From this work, we generate automated real-time plots of  $L$  measurements at 1-minute, 1-hour, and 6-hour time scales and the corresponding GCR spectral index at 10.5 GV (see <https://neutronm.bartol.udel.edu/realtime/southpole.html> and [https://neutronm.bartol.udel.edu/~pyle/json/SOPO\\_RTLF.html](https://neutronm.bartol.udel.edu/~pyle/json/SOPO_RTLF.html)). The GFA technique also can be performed at near real-time as a cross check. Understanding FDs is important for space weather forecasting and radiation risk assessment. Since cosmic rays can affect satellite electronics, communication systems, and even airline crew and passengers at high altitudes [12], predicting these decreases helps mitigate potential disruptions. Additionally, studying Forbush decreases provides valuable insights into solar-terrestrial interactions and the structure of magnetic fields in interplanetary space.

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<sup>1</sup>[doi:10.7910/DVN/C2MHTH](https://doi.org/10.7910/DVN/C2MHTH)

<sup>2</sup><http://isgi.unistra.fr>

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