Time variations in Galactic cosmic rays as measured from Southeast Asia

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Abstract. We summarize time variations in Galactic cosmic ray (GCR) measurements from the Princess Sirindhorn Neutron Monitor (PSNM) at the summit of Doi Inthanon, Thailand’s highest mountain, since 2007. PSNM is the first neutron monitor (NM) station making long-term measurements in Southeast Asia, with the world’s highest cutoff (threshold) rigidity (momentum per charge) of \(\approx 17\) GV. GCR variations with the ~11-year sunspot cycle or ~22-year solar magnetic cycle are known as solar modulation. Compared with measurements at lower cutoff, PSNM reveals a distinct pattern of solar modulation related to the interplanetary magnetic field strength. NM viewing directions rotate with Earth, so daily (“diurnal”) variations indicate the GCR anisotropy, and we identified time intervals with unusually strong anisotropy due to a unidirectional GCR gradient. From worldwide NM data, we determine an hourly anisotropy during GCR decreases associated with solar storms, indicating GCR flows consistent with our previous theory that cosmic rays drift into one leg of an interplanetary flux rope and out the other. PSNM was also the first fixed NM to monitor time delays between successive neutrons, providing a proxy for the cosmic ray spectral index using data from a single station, avoiding the systematic uncertainties of cross-station comparisons.

1. Introduction
Cosmic rays are energetic particles or gamma rays from space. As such, they represent the high-energy radiation environment in near-Earth space. There are two main sources of cosmic rays: Our Sun, and supernovae throughout our Galaxy. The Sun produces energetic particles due to occasional sudden explosions at its surface, called solar storms, which can accelerate particles to relativistic energies (ions up to tens of GeV, electrons up to tens of MeV) for durations up to about an hour. Furthermore, a type of storm called a coronal mass ejection (CME) can drive an interplanetary shock that accelerates ions up to tens of MeV (called “energetic storm particles”) as it travels outward [1-4]. The particles due to solar storms, collectively called solar energetic particles (SEPs), pose a major radiation hazard to astronauts [5] and some risk to humans in airplanes [6-8] for short but unpredictable time periods, as well as damaging expensive satellites and spacecraft (at least fifteen have been disabled by solar storms to date). These and other effects of solar storms (including ionospheric disturbances, geomagnetically induced currents, and power outages) are called “space weather” effects.

On the other hand, the continuous flux of Galactic cosmic rays (GCRs) contributes more to ionizing radiation at Earth’s surface [8]. When interacting in Earth’s atmosphere, high energy GCR ions (from \(~1\) GeV \(= 10^9\) eV up to \(~10^{19}\) eV) produce secondary particles that can propagate to ground level. Figure 1 schematically indicates the so-called shower of secondary particles that can result,
including an electromagnetic shower component \((e^\pm, \gamma)\), muons \((\mu^\pm)\), and nucleons \((p \text{ and } n)\). This secondary radiation

Figure 1. Schematic of a cosmic ray shower in Earth’s atmosphere, indicating electromagnetic, muon, and nucleon components. Yellow circles indicate interactions involving a nucleus in the atmosphere. Ground-based muon detectors have the advantage that they can measure the muon flux in various directions, relating to the cosmic ray flux from different ranges of directions in space. Neutron monitors (NMs) detect neutrons in order to study GeV-range cosmic rays, with the advantages of a clear correction for atmospheric effects (the pressure correction) and a count rate that is mostly sensitive to the cosmic ray flux near the geomagnetic cutoff (threshold). The global NM network includes NMs at different locations, providing information about the cosmic ray flux above a cutoff that varies from \(~1\) to \(17\) GV. Adapted from [9].

was a key driver of biological mutations and evolution, and the primary GCRs would be a serious hazard to astronauts on long-duration missions outside the Earth’s magnetosphere. The flux of GCRs is also sensitive to the solar wind speed and solar activity and may even offer a way to provide advance warning before the arrival of an interplanetary shock and its associated spaceweather effects [10-11].

Ground-based detectors of atmospheric secondary particles from cosmic rays can provide useful information on space physics with a much lower budget than space missions. Indeed, the most energetic cosmic rays, above \(~10^{15}\) eV, are almost always detected by means of their shower particles using large “air shower arrays” with many component detectors. For detection of cosmic ray ions at GeV-range energies, smaller ground-based detectors of muons and neutrons have a special niche: to precisely measure time variations in the GCR flux. These variations are due to solar storms and variations in solar wind speed and interplanetary magnetic field (of solar origin), as will be described in detail below.
Muons can be detected by two sets of detectors in coincidence (often with metal in between to absorb less penetrating electrons and positrons), with the advantage that their direction is correlated with the direction of the primary cosmic ray. Thus an array of muon detectors in layers can provide information on the cosmic ray flux from various directional ranges in space. Muon detectors at Earth’s surface are typically sensitive to a median primary cosmic ray rigidity (defined by $P = pc/q$, where $p$ is the particle momentum and $q$ is its charge) of ~60 GV for nearly vertical arrival directions [12]. The mean rigidity of detected GCRs is higher for muons with higher zenith angle or for underground muon detectors.

This article mainly concerns another type of ground-based cosmic ray detector called a neutron monitor, first developed in 1948 by the late J. A. Simpson at the University of Chicago [13]. As the name suggests, this type of detector monitors time variations in the count rate of neutrons produced by cosmic ray showers.

2. Princess Sirindhorn Neutron Monitor

Our research team at Mahidol University, Ubon Ratchathani University, and Chulalongkorn University in Thailand installed the Princess Sirindhorn Neutron Monitor in 2007 at the summit of Doi Inthanon, Thailand’s highest mountain, at latitude 18.59°N and 98.49°E at altitude 2560 m (see Figure 2). This uses the standard NM64 design (see Figure 3) with 18 neutron counter tubes, which can also be called an 18NM64 or a “supermonitor.”

A key component of this 18NM64 is 29 tons of 99.99% pure lead “rings with wings,” in which a cosmic-ray-generated atmospheric secondary particle, typically an neutron of 10 MeV to 10 GeV, can disrupt a lead nucleus to produce several low-energy neutrons. Thus we call this lead the “producer.” Polyethylene (PE) is used simply as a relatively inexpensive solid compound with a high density of hydrogen, the element that most effectively moderates neutrons because the hydrogen nucleus (proton) and neutron have similar masses, e.g., a single head-on collision could transfer almost all of the neutron’s energy to the proton. Neutrons of >10 MeV typically pass through the PE without interacting, but low-energy neutrons are efficiently moderated toward the thermal energy range. The 3-inch PE reflectors surrounding the monitor serves to block low-energy neutrons from the environment (which are sensitive to water, temperature, movement of surrounding materials, etc.) while trapping most neutrons produced by interactions in the lead. There is also a PE moderator of cylindrical shape surrounding each proportional counter (PC) tube. These tubes contain $^{10}$BF$_3$ gas in which neutrons (especially those at low energy) induce nuclear fission of $^{10}$B by the reaction $n + ^{10}$B $\rightarrow ^{7}$Li + $^4$He. This releases over 2.3 MeV of kinetic energy, yielding a strong signal that unambiguously indicates a neutron detection.

![Figure 2. Left: Princess Sirindhorn Neutron Monitor station at the summit of Doi Inthanon, Thailand’s highest mountain (at 2560 m altitude). Right: View inside the station, showing the 18-tube neutron monitor of standard NM64 design (right) and two bare neutron counters (center).](image-url)
Figure 3. Components of a neutron monitor of standard NM64 design, shown in cross-section (to scale). PE = polyethylene, PC = proportional counter. Adapted from [14].

Figure 2 shows that we also operate bare neutron counters in the PSNM station, which lack the PE reflector and lead producer. We find that the count rate from a PC in the 18NM64 detector is ≈6 times higher than the count rate from a bare counter, implying that the lead plays a major role in capturing atmospheric secondaries from cosmic ray showers and producing more neutrons, which are trapped by the PE reflector.

Indeed, it is scientifically necessary to have a high count rate, because the main purpose of the NM is to measure time variations in the cosmic ray flux. Some of these variations are ~1% or less, and some occur on time scales less than one day, so our target precision is 0.1% for hourly rates. Like any experiment that counts $N$ particles arriving randomly, we have a statistical uncertainty of about $N^{1/2}$ (with a small correction for “multiplicity,” the correlated detection of multiple neutrons associated with the same cosmic ray shower). Then the relative statistical uncertainty is about $N^{-1/2}$, and to achieve 0.1% accuracy requires over a million neutron counts per hour. The count rate can be boosted by using a large number of PC tubes. Furthermore, the altitude is very important, because the nucleon component of a cosmic ray shower is rapidly absorbed with increasing atmospheric depth. We found that the count rate of a bare counter at the summit of Doi Inthanon, with altitude 2560 m, is about 6 times higher than the rate observed at Mahidol University in Bangkok (nearly at sea level). As a result of its mountain top location and large number of counter tubes, PSNM typically detects 2.2 million neutrons per hour, allowing us to achieve <0.1% statistical precision. Note that for collection times less than one hour the uncertainty is greater, and when averaging over multiple hours or days the uncertainty is even lower.

In addition, great care is taken to avoid systematic uncertainties and to maintain stable operation, especially because some of the variations we study occur over the ~11-year solar activity cycle. Furthermore, atmospheric effects are greater than the desired level of precision. As noted above, nucleons are absorbed in Earth’s atmosphere, and changes in the measured count rate are anti-correlated with changes in pressure, which approximately measures the weight per area of the overlying atmosphere. Compared with other types of cosmic ray shower detectors, neutron monitors have an advantage of a clean atmospheric correction: a simple pressure correction mostly removes atmospheric effects, and such a correction is common practice in the community. However, we recently reported evidence that the atmospheric water vapor also affects PSNM data [14], causing a small seasonal wave (0.3%) in the count rate in association with the rainy season in Thailand [15].

Another key advantage of NMs, as noted in Figure 1, is that their response to primary cosmic rays peaks at a rigidity of about 5 GV [16], which is in the range where Earth’s magnetic field serves as a rigidity-selective magnetispectrometer. Therefore, NMs have been set up in various locations around the world, and each of them is sensitive to primary cosmic rays in a different rigidity
range. Note that the trajectory of a particle in a magnetic field depends only its rigidity, and not the type of particle. Indeed, for an NM or muon detector we do not know the element or mass of the primary cosmic ray, but we do know that its rigidity must exceed the “cutoff” (threshold) rigidity $P_c$ for a given location and arrival direction.

Figure 4 shows the worldwide locations of NMs operating in 2010 (red dots) as well as contours of effective vertical geomagnetic cutoff rigidity $P_c$ (in GV). South and Southeast Asia is a special location, close to the Earth’s magnetic equator and the offset dipole center. Southeast Asia has the world’s highest cutoff rigidity, at about 17 GV, so measurements here are unique and provide information about more energetic GCRs than NMs at other locations. For completeness, it should be noted that there is also an atmospheric cutoff of $\sim$1 GV for cosmic rays to produce shower particles that can be observed at ground level. Therefore, in Earth’s polar regions the cutoff rigidity is determined by the atmospheric cutoff rather than the geomagnetic cutoff. Effectively, the cutoff rigidity at Earth’s surface varies from $\sim$1 to 17 GV, so this is the range that can be explored by comparing the NM count rate vs. time at different locations.

![Figure 4](image)

**Figure 4.** Locations of neutron monitor stations in the global network, along with contours of constant effective vertical geomagnetic cutoff rigidity in GV. Southeast Asia is a unique location with the world’s highest cutoff rigidity. Courtesy of R. Pyle.

Fixed NM stations can be very stable with time, and some stations have provided a nearly continuous, precise record of the cosmic ray flux for several decades. Most stations make their data publicly available, and a particularly convenient site for downloading and plotting data is the Neutron Monitor Database (http://nmdb.eu). Another useful technique is to operate an NM on a ship that crosses a wide range of cutoff rigidities over a few weeks or months. Such “latitude surveys” can measure the response function of the neutron monitor, though some care is needed to determine corrections for pressure and cosmic ray flux variations. Repeated NM latitude surveys allow us to very precisely determine changes in the cosmic ray flux [16-17]. Latitude surveys have also been performed for bare neutron counters [18-20].
PSNM is the first neutron monitor (NM) station making long-term measurements in Southeast Asia (since 2007 December in its full configuration). There was a previous NM near Southeast Asia at Lae in what is now Papua New Guinea, at a cutoff of about 15 GV. Data from the Lae NM are available from 1957 and 1964 [15], when there were concerted worldwide campaigns to collect NM data around the world. Among currently operating NMs, PSNM has the world’s highest effective vertical cutoff rigidity of 16.7 GV. There was previously an NM station with a slightly higher cutoff rigidity at Kodaikanal in India, for which data are available for about 1957-1959 and 1964.

To properly understand the response of PSNM to cosmic rays, our team has performed detailed Monte Carlo simulations of particle interactions in Earth’s atmosphere to determine the distributions of secondary cosmic rays, and also interactions of such secondary particles in the PSNM station [21, 22], using the FLUKA simulation program [23]. These simulations can reproduce the PSNM count rate at Doi Inthanon to within 9%. They indicate that 63.1% of the NM count rate is due to secondary neutrons between 10 MeV and 1 GeV. Another 15.7% is due to neutrons over 1 GeV and 15.3% is due to protons. Negative muons (which can disrupt a lead nucleus by forming a muonic atom in which the muon’s Bohr orbital is inside the nucleus), neutrons below 10 MeV, and photons each contribute 1-2% [21].

3. Time variations of Galactic cosmic ray flux

3.1. Overview
The key goal of a neutron monitor is to measure cosmic ray variations due to solar phenomena (Figure 5). There are various types of variations in the GCR flux, as follows: There are “diurnal” (daily) variations associated with Earth’s rotation with respect to the Sun, which sweeps a ground-based detector’s look directions around the sky. Diurnal variations are associated with the anisotropy of GCRs, a slight imbalance in the GCR flux arriving from different directions in space. There are 27-day variations based on a roughly inverse relationship between the solar wind speed and the GCR flux. Effectively, a faster solar wind inhibits Galactic cosmic rays from entering the inner solar system, to some extent. Different regions of the solar corona produce fast or slow solar wind, so these patterns approximately repeat over the synodic solar period of about 27 days (hence these are also called synodic variations [24]). The longest-period cosmic ray variations that are directly measured relate to the ~11-yearsunspot cycle and the ~22-year solar magnetic cycle, collectively known as solar modulation of GCRs. Most of these variations will be described in more detail in the following subsections. Note that in general, time variations in the GCR flux are stronger at lower rigidity because the solar wind and solar storms have much less effect on more energetic particles.

There are also transient GCR decreases due to solar storms, and in particular, the passage of a coronal mass ejection (CME) or associated shock, which can block the inward transport of GCRs. These events are known as Forbush decreases after their discoverer [25]. There is often a first-stage decrease associated with the shock arrival, and there may also be a second stage associated with the arrival of the CME ejecta, with a further decrease that lasts while the ejecta pass the observer. After that, the GCR flux returns to normal over the next few days. It is common to observe interesting anisotropy patterns during a Forbush decrease, which may indicate interesting directional distributions of particles following the magnetic structures of the CME.
Figure 5. Hourly count rate (in s$^{-1}$) of the Princess Sirindhorn Neutron Monitor at Doi Inthanon, Thailand, which tracks the Galactic cosmic ray (GCR) flux above $\sim$17 GV, since 2007 December. There are variations due to the $\sim$11-year solar cycle, 27-day variations associated with solar rotation, and short-term decreases associated with the passage of solar storms (coronal mass ejections). On a shorter time scale, there are also daily (diurnal) variations due to Earth’s rotation, indicating the GCR anisotropy. Plotted using the NMDB Event Search Tool (http://www.nmdb.eu/nest/).

So far, PSNM has only detected Galactic cosmic rays. It is at a good location to potentially detect solar neutrons in the future. Solar neutrons are not affected by Earth’s magnetic field; rather, detection of showers from solar neutrons depends strongly on the atmospheric depth [26]. This favors an NM at low latitude and high altitude, with detection most likely within a few hours of local noon. Most detections of solar neutrons have been associated with X-class solar flares, which are relatively rare. It is also possible for NMs to detect solar energetic ions; such an event is known as a ground-level enhancement, indicating such a high flux of GeV-range SEPs that their showers cause a count-rate enhancement above the pre-existing level due to GCRs. In terms of solar effects on Earth’s radiation environment, the relevant solar storms are these GLEs, which are relatively rare because only a few solar storms can accelerate SEPs to such energies in significant numbers. There were 15 or 16 GLEs in the two previous solar cycles, but there were only 4 events (and no strong events) in the outgoing Solar Cycle 24. In any case, in the NM era the only GLEs observed at high cutoff rigidity were on 1956 February 23 [27] and 2005 January 20 [28], so we may have to wait for $\sim$50 years for a GLE to be detected by PSNM.

3.2. Solar modulation

As mentioned above, solar modulation refers to GCR variations with the $\sim$11-year sunspot cycle or $\sim$22-year solar magnetic cycle. Because magnetic fields and solar storms are concentrated near sunspots, numerous solar phenomena vary with the sunspot cycle, which can also be called the “solar activity cycle” or simply “solar cycle.” In addition, the solar wind speed and magnetic fluctuations also tend to be stronger with solar activity, but do not precisely depend on the sunspot number, so we tend
to speak of “solar maximum” as a period of several years around solar maximum, and “solar minimum” as a period of several years with very few sunspots (including the time of writing, 2019 August). Because of the faster solar wind speed, stronger magnetic fields and magnetic irregularities, and more frequent CMEs during solar maximum, the transport of cosmic rays to the inner heliosphere is inhibited to some extent. Thus the flux of cosmic rays is observed to have an inverse association with the sunspot number, with the most cosmic rays during solar minimum and the fewest during solar maximum.

Figure 5 shows the variation in cosmic ray flux observed by PSNM since 2007 December. The cosmic ray maximum in 2009 corresponded to the sunspot minimum of 2008, with a delay of ~1 year that is presumably associated with the propagation of the solar wind to the outer reaches of the heliosphere. (Note that what appears as a double maximum during 2009 in Figure 5 is affected by atmospheric water vapor at Doi Inthanon; when correcting for the 0.3% minimum-to-maximum seasonal effect of water vapor, there is only a single maximum in 2009 [15].) Then the cosmic ray minimum at the end of 2014 was associated with sunspot maximum (Cycle 24), and the recent cosmic ray maximum in 2018 corresponds to the ongoing solar minimum conditions (end of Cycle 24).

The Sun’s magnetic field is much more complex than the Earth’s, and magnetic fields are highly concentrated at the sunspots, typically directed outward at one and inward at another. Nevertheless, there is an overall preponderance of one polarity on one hemisphere and the opposite polarity on the other; the dividing line can be modeled as a great circle with a tilt angle relative to the solar equator. As the Sun rotates and the solar wind carries out the solar magnetic field to become the interplanetary magnetic field (IMF), this dividing line becomes a wavy current sheet, still approximately characterized by a tilt angle. Amazingly, at every solar maximum, there is a magnetic polarity reversal in which the tilt angle becomes high, the magnetic polarity reverses sign at the Sun’s poles, and the tilt angle decreases again. Therefore, a complete magnetic cycle requires 2 sunspot cycles, i.e., about 22 years. Charged particle orbits undergo drift motions that depend on the charge sign and the sign of the magnetic field. For a given type of particle, e.g., GCR ions, the drifts therefore reverse every 11 years and repeat every 22 years [29]. The same holds for the effect of magnetic helicity on the particle scattering, and there are clear 22-year features in both the flux and the anisotropy of GCRs [30]. In addition to solar modulation with the 11-year solar cycle, latitude survey data reveal that the shape of the GCR spectrum is somewhat different for opposite solar magnetic polarities [17, 20].

Observations of solar modulation provide important and arguably unique information about the global properties of the heliosphere, because GCRs reach Earth after traveling over a great range of distance, heliolatitude, and heliolongitude. Their transport is affected by the IMF and tilt angle, magnetic turbulence, and solar wind speed over a large heliospheric volume. It has long been known that the amplitude of solar modulation is weaker at higher cutoff rigidity. For PSNM, with an effective vertical cutoff rigidity of 16.7 GV, the maximum-to-minimum change in count rate with solar modulation over Cycle 24 was ≈2.3%. In contrast, at McMurdo station in Antarctica, corresponding to a cutoff rigidity of ~1 GV, this change was ≈15% [15].

In our team’s latitude survey analyses, we found that while the tilt angle was not high, the NM count rate at various cutoff rigidities exhibited a linear relationship with the McMurdo count rate at low cutoff, with a slope that changed with solar magnetic polarity [20]. In our recent work comparing PSNM data at high cutoff rigidity and McMurdo data at low cutoff rigidity [15], for low tilt angle we confirmed such a linear relationship. However, for high tilt angle (from early 2011 to early 2014), we discovered a distinct pattern of solar modulation for PSNM at high cutoff rigidity; in this case the overall solar modulation over Solar Cycle 24 was closely related to the interplanetary magnetic field strength. Taking into account the ~1-year delay time for propagation of solar effects to the outer heliosphere, this time period of high tilt angle corresponded to negative magnetic polarity in the Sun’s northern hemisphere. For this negative polarity, GCR ions are believed to drift inward along the wavy current sheet, and as the tilt angle increases, their path becomes longer and more subject to outward convection and scattering. This is qualitatively consistent with the gradually decreasing McMurdo count rate at low cutoff rigidity. Given that the PSNM count rate exhibits a different pattern of
modulation, with the count rate remaining high, and that the diffusion coefficient corresponding to scattering from magnetic irregularities should be higher at higher particle rigidity, we propose that for high rigidity GCR ions, diffusion can short-circuit the long, convoluted path of the drift motion that may inhibit GCR ions of lower rigidity from entering the inner heliosphere. This is consistent with the overall dependence of the PSNM count rate on the IMF, since the diffusion coefficient should be inversely related to magnetic field strength.

4. Galactic cosmic ray anisotropy
A single NM measure the GCR anisotropy by means of the daily variation with Earth’s rotation as described above. This is often called the “diurnal anisotropy” (or more specifically, “solar diurnal anisotropy” as distinguished from sidereal diurnal anisotropy). At Doi Inthanon, such variations are less than 1%, and are somewhat difficult to measure on a day-to-day basis, but are clear over trains of several days and precisely measured over time periods of years. On average, the anisotropy indicates a cosmic ray flow directed along Earth’s orbit, impacting the Earth from behind. This is consistent with a “corotational anisotropy” due to a balance between outward convection with the solar wind and inward diffusion along the IMF, leading to a cosmic ray distribution that is roughly isotropic with respect to the Sun’s magnetic field lines and therefore corotating with the Sun [31]. In one project, we identified time intervals with unusually strong anisotropy at times when the IMF was directed away from the Sun, and weak anisotropy when it was toward the Sun [24]. We attribute this to a corotational anisotropy with a superposed gradient anisotropy. The latter occurs because cosmic ray ions gyrate around the IMF, and when there is a gradient in the cosmic ray density, an observer detects an anisotropy in a direction perpendicular to both that gradient and the IMF. Thus the gradient anisotropy reverses with a reversal in the IMF direction, and is particularly strong for the high cutoff rigidity at PSNM, corresponding to a large particle gyroradius. We proposed that a latitudinal cosmic ray gradient was generated by a slanted, merged high-speed solar wind stream associated with coronal holes at the Sun.

In a more recent study, we combined data from PSNM and numerous other NMs viewing different directions in space, to determine the cosmic ray anisotropy on an hourly basis [32] during a Forbush decrease (FD) associated with the passage of a shock, a sheath region with times of strong turbulence, and a magnetic flux rope from a CME. Cosmic-ray observations during FDs can provide information complementary to in situ observations of the local plasma and magnetic field, because cosmic-ray distributions allow remote sensing of distant conditions. We therefore developed techniques to determine the GCR anisotropy before and during an FD using data from the worldwide network of neutron monitors, for a case study of the FD starting on 2013 April 13. We found that at times with strong magnetic fluctuations and strong cosmic-ray scattering, there were spikes of high perpendicular anisotropy and weak parallel anisotropy. In contrast, within the CME flux rope there was a strong parallel anisotropy in the direction predicted from our previous theory of drift motions into one leg of the magnetic flux rope and out the other [33], confirming that the anisotropy can remotely sense a large-scale flow of GCRs through a magnetic flux structure.

5. Leader fraction as indicator of cosmic ray spectral index
In another line of work, we have pursued techniques to determine the spectral index of GCRs using data from a single NM station, avoiding the systematic uncertainties of cross-station comparisons. Previous work has examined neutron time delay histograms from NM counter tubes [34-36], as recorded by specially designed readout electronics at selected NMs. Here the time delay refers to the time interval between successive neutron detections in one counter. Bieber et al. [34] stated that time delays over 2 ms are dominated by chance coincidences, with an exponential distribution characteristic of unrelated events, while shorter time delays are mostly due to the correlated arrival of neutrons from the same nuclear interaction, typically an interaction in the lead producer. We then collaborated with that group to implement their readout electronics at PSNM, and we developed an analysis technique to statistically remove the effect of chance coincidences and measure the “leader
fraction” $L$ of neutrons that do not follow a previous neutron from the same primary cosmic ray [14]. Here $L$ is a measure of the inverse multiplicity and increases for increasing GCR spectral index. The raw value of $L$ exhibits an annual wave, which we found to be well explained as a dependence on atmospheric water vapor and atmospheric pressure. After correcting for these effects, we found that $L$ indicates substantial short-term GCR spectral hardening during some but not all Forbush decreases in GCR flux due to solar storms. Such spectral data from Doi Inthanon provide information about cosmic-ray energies beyond the Earth’s maximum geomagnetic cutoff, extending the reach of the worldwide NM network and opening a new avenue in the study of short-term GCR decreases.

To verify that the leader fraction $L$ can actually indicate changes in the cosmic ray spectrum, we performed an analysis of $L$ as measured by these special electronics during six yearly latitude surveys during 2001-2007 [37]. We compared the observed results as a function of cutoff rigidity with the results of Monte Carlo simulations. Though there was a slight offset in the absolute values of $L$, the relative changes agreed very well and even reflected the effects of solar modulation. This verifies that $L$ varies according to changes in the cosmic ray spectrum.

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