Cosmic Rays, Atmospheric Ionization, and Clouds

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We study cosmic rays:

- Energetic particles or gamma rays from space
- Ordinary matter accelerated to high energies
- \( p, \ ^4\text{He}, \ ^{12}\text{C}, \ ^{16}\text{O}, \ldots \) (ions) \( e^-, \gamma, \mu^+, \mu^-, n, \ldots \)
- Possible effects on Earth’s climate??
- Sources of cosmic rays (energetic particles)
  - inside the solar system (e.g., solar energetic particles, from solar storms)
  - outside the solar system (e.g., Galactic cosmic rays)

IN BOTH CASES, VARIATIONS ARE DUE TO SUN

Image credit: www.invisiblemoose.com (WALTA group)
When an energetic cosmic ray comes to Earth ...

"Primary" cosmic ray
(a particle from space)

We measure the neutrons!

[key: P Proton, e Electron, n Neutron, p Pion, μ Muon, γ Photon]
Neutron Monitor (NM-64 design)

PC = \textsuperscript{10}BF\textsubscript{3} proportional counter

PC wire    PC wall

PE reflector

PE moderator
(PE=polyethylene)

Wood

\textit{Atmospheric secondary particle (usually a neutron)}

\textbf{n} + \textsuperscript{10}\textbf{B} \rightarrow \textsuperscript{7}\textbf{Li} + \textsuperscript{4}\textbf{He}

Provides accurate count rate, related to cosmic ray flux in space. Altitude is extremely important, so we aim high ...

[Ruffolo et al. 2016]
Low-energy cosmic rays only reach Earth’s polar regions; higher energy is needed to penetrate equatorial B field.

Locations of neutron monitors and their cutoff rigidities in GV.

Rigidity is $pc/q$, determines particle trajectory in magnetic field.

Solar particles mostly come here...

...and here.
The 11-year sunspot cycle …

… and 22-year solar magnetic cycle seen in galactic cosmic ray flux

[Nuntiyakul et al. 2014]
Historical observations, since 1610 (sunspots also recorded in ancient times)

Overview of Our Research

Work at MU, CMU, KMUT-NB, TU, KU, CU, UBU, PIM, NARIT
Ultimate goal of work with NARIT: Observationally test whether solar cycle affects Earth’s climate via cosmic rays, atmospheric ionization, and clouds. Svensmark et al. (2009) claimed to observe a short-term (few days) connection between cosmic rays and clouds.

The Princess Sirindhorn Neutron Monitor (PSNM) at the summit of Doi Inthanon precisely tracks cosmic ray flux with world’s highest cutoff rigidity – relevant to atmospheric ionization.

Also need spectrum, to relate that flux to other energies, and Monte Carlo simulations of atmospheric showers & ionization.
Present stage (1):

With our newly developed “leader fraction” \((L)\) based on NM data from specialized electronics, we have precisely tracked variations in the spectral index of Galactic cosmic rays over a solar modulation cycle from Dec., 2007 to 2018

[Banglieng et al., Siam Physics Congress (2018), journal article to be prepared soon]
Tracking spectral changes in Galactic cosmic rays: Neutron time delays

[Bieber et al. (2004), Ruffolo et al. (2016)]

New analysis technique: Removing chance coincidences …

… to find the “leader fraction”
Doi Inthanon Leader Fraction (18 neutron counter tubes)

Time period 1  Time period 2  Time period 3  Time period 4  Time period 5  Time period 6  Time period 7  Time period 8  Time period 9

Date (UT) 1/1/2008 1/1/2010 1/1/2012 1/1/2014 1/1/2016 1/1/2018
Leader Fraction and Count Rate vs. time

PSNM at Doi Inthanon

South Pole
Leader Fraction vs. Count Rate at PSNM
Present stage (2):
We have developed accurate Monte Carlo simulations of the NM count rate \((C)\) and leader fraction \((L)\) and stringently tested them with data from the PSNM at Doi Inthanon and from a latitude survey during 2001-2007 [Mangeard et al. 2016a,b] -> Finished.
Present stage (3):
In order to determine the response function of bare neutron counters to primary cosmic rays, which underlies a key technique for determining spectra of solar energetic particles, we have analyzed data from bare counters and a NM on a latitude survey during 1995 [Nuntiyakul et al., submitted].
Measured bare & NM response functions vs. cutoff rigidity [Nuntiyakul et al.]
Measured bare & NM response functions vs. cutoff rigidity [Nuntiyakul et al.]
Present stage (4):
Based on NM data, we already estimated the atmospheric ionization and biological dosage due to the giant solar storm of 2005 Jan 20 [Mitthumsiri et al. 2017].
There was essentially no new cloud formation at location of strong ionization (Antarctica), so we are investigating whether we can constrain cloud formation mechanisms [Sakulsupich et al., Thai Space Physics 2018].
Simulating the Nucleation Process

We simulate the nucleation rate based on the ion-mediated nucleation model developed by Fangqun Yu in 2010.

\[ J = J(T, Q, RH, S, A) \]

\[ J = \text{Nucleation rate (cm}^{-3}\text{ s}^{-1}) \]
\[ T = \text{Temperature (K)} \]
\[ Q = \text{Ionization rate (ion-pair cm}^{-3}\text{ s}^{-1}) \]
\[ RH = \text{relative humidity (\%)} \]
\[ S = \text{sulfuric acid vapor concentration (cm}^{-3}) \]
\[ A = \text{surface area of pre-existing aerosols (\mu m}^2\text{ cm}^{-3}) \]
Nucleation Rate Dependence on Ionization Rate

\[ J = J(T, Q, RH, S, A) \]

- **T** = Temperature
- **Q** = Ionization rate
- **RH** = Relative humidity
- **S** = [H2SO4]
- **A** = Surface area of pre-existing aerosols

Fangqun Yu (2010)
Output of this project (1):


(Researchers working in Thailand in bold type, 2016 impact factors in parentheses, asterisk indicates corresponding author.)
Output of this project (2):


(Researchers working in Thailand in bold type, 2016 impact factors in parentheses, asterisk indicates corresponding author.)
Output of this project (3):


(Researchers working in Thailand in bold type, 2016 impact factors in parentheses, asterisk indicates corresponding author.)
SPARE SLIDES
Smoothed Sunspot Number Monthly Averages

Source: WDC-SILSO, Royal Observatory of Belgium, Brussels
http://sidc.be/silso/datafiles

Thule, Greenland, Neutron Monitor
Bartol Research Institute, University of Delaware
27-day Averages - data through June 2016

R. Pyle, June 2016
Comparing time profiles from two NM stations at different cutoff rigidity (energy) does not provide a good estimate of spectral variations.

Figure 2. Comparison of daily count rates from 2007 December to 2011 February from the Yangbajing and Doi Inthanon NMs at vertical cutoff rigidities of about 13.8 and 16.8 GV, respectively, along with the count-rate ratio. Each NM count rate has precise statistical accuracy (better than 0.02%). Variations in the count-rate ratio might be expected to indicate changes in the cosmic-ray spectrum. While the long-term rise and fall in the ratio are consistent with the known spectral softening near sunspot minimum (GCR maximum), shorter-term variations seem to have a systematic uncertainty and do not clearly indicate the known spectral hardening during short-term decreases. In the present work, we develop a method to study short-term spectral variations using a single NM, without the systematic uncertainty of a station-to-station comparison.

[From Ruffolo et al. (2016)]
Tracking spectral changes in Galactic cosmic rays: Neutron time delays

[Bieber et al. (2004), Ruffolo et al. (2016)]

New analysis technique: Removing chance coincidences …

… to find the “leader fraction”
First precision tracking of short-term changes in spectrum of Galactic cosmic rays

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Figure 3. Illustration of the geometry for Monte Carlo simulations of the calibrator outside but nearby the PSNM building at Doi Inthanon, Thailand. It was set above a swimming pool on top of a bunker and operated for various water heights and calibrator heights during November 2009 to June 2010.
For radiation dose in Earth’s atmosphere, particle anisotropy can be a major factor in SEP events.

[Image credit: J. W. Bieber]
[Mitthumsiri et al., in press]

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Example of a Forbush decrease in Galactic cosmic rays due to a solar storm
We have developed state-of-the-art Monte Carlo modeling of Galactic cosmic ray primary particle (PP) interactions in the atmosphere to make secondary particles (SP) ... followed by modeling SP interactions in the neutron monitor [Mangeard et al. 2016a]

We use the FLUKA simulation code
Our “galaxy cluster”
(40+ nodes, 4 or 6 cores per node)
Figure 2. Illustration of the geometry for Monte Carlo simulations of the calibrator inside the PSNM building at Doi Inthanon, Thailand. This cutaway view removes most of the east wall. The calibrator (white cylinder at right) was operated inside the station during June 2010. The 18-tube NM64 neutron monitor (left) and three bare neutron counter tubes (front) have been operating there since 2007. Spare lead rings are kept in a storage room to the right. [Aiemsa-ad et al. (2015)]
Monte Carlo results are within 9% of NM count rate at Doi Inthanon (standard in field is ~25%).

This graph shows tube-to-tube variations in data (black) and Monte Carlo (red), due to electronic dead time and detector position.

Figure 7. Count rate of each PSNM neutron counter tube relative to the tube average and measured electronic dead times. Observations are represented by filled circles. Simulated values are represented by filled squares. Dead time values are represented by open triangles. There are clear effects of the tube position relative to the edges of the row of 18 counter tubes and the dead time.

[Mangeard et al. 2016a]
For latitude survey years 2001-2006, Monte Carlo results provide a good explanation of the leader fraction vs. cutoff rigidity and changes with time due to solar cycle. [Mangeard et al. 2016b]

**Figure 3.** Dependence of the leader fraction $L$ measured by the mobile neutron monitor on the apparent cutoff rigidity $R_c$ for the six surveys operating with the same firmware, together with the range of Monte Carlo results for various cosmic ray spectra and atmospheric profiles. This confirms that the observed $L$ is related to the rigidity spectrum of primary cosmic rays impinging on Earth’s atmosphere. Note the overall dependence on time at a given $R_c$, which is clearest at low $R_c$, reflecting the variation of the cosmic ray spectrum with the sunspot cycle, known as solar modulation. Monte Carlo results reproduce those trends but slightly underestimate the absolute value of $L$. 

[Mangeard et al. 2016b]

Figure 1. Tracks of the shipborne neutron monitor latitude surveys from 2000 to 2007, superimposed on contours of the vertical cutoff rigidity in GV. The year of a survey refers to the year in which it started.
For latitude survey years 2001-2006, Monte Carlo results provide a good explanation of leader fraction variation with cutoff rigidity (due to cosmic ray energy distribution) and with time (due to solar cycle effects on cosmic ray spectrum).  [Mangeard et al. 2016b]

**Figure 13.** Dependence of the leader fraction $L$ measured by the mobile neutron monitor on the apparent cutoff rigidity $R_c$ for the six surveys operating with the same firmware, together with the range of Monte Carlo results for various cosmic ray spectra and atmospheric profiles. Observations were normalized relative to the leader fraction for the 1–2 GV cutoff rigidity bin for survey year 2006 (0.851). Simulation results are normalized to the calculated leader fraction at $R_c = 1$ GV using PAMELA spectra and the Sea11 atmosphere (0.843).