Measuring the Cosmic Ray Spectrum Using Neutron Monitors

Next Generation Advances in Ground-Based Solar Physics

A Decadal Preparation

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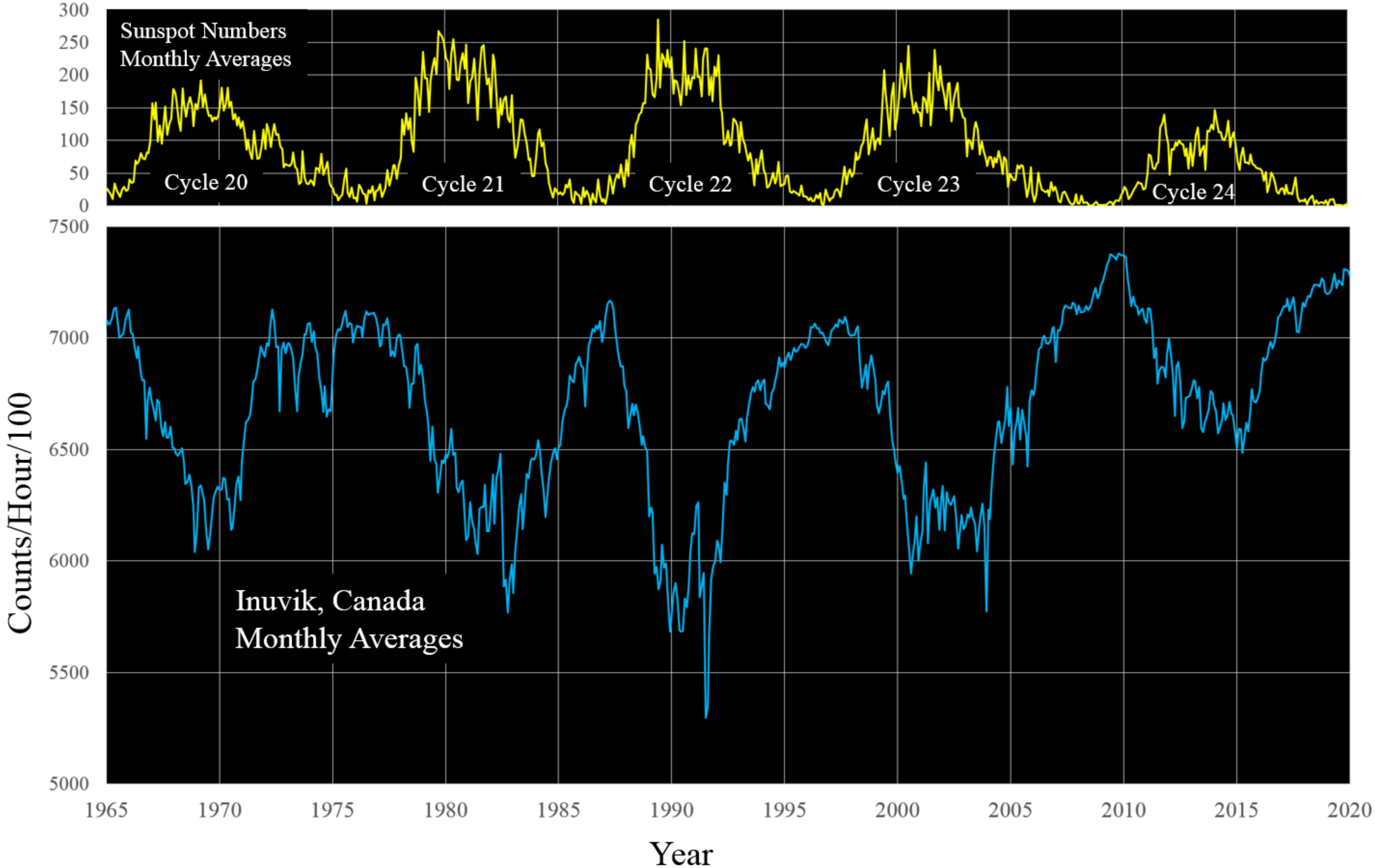
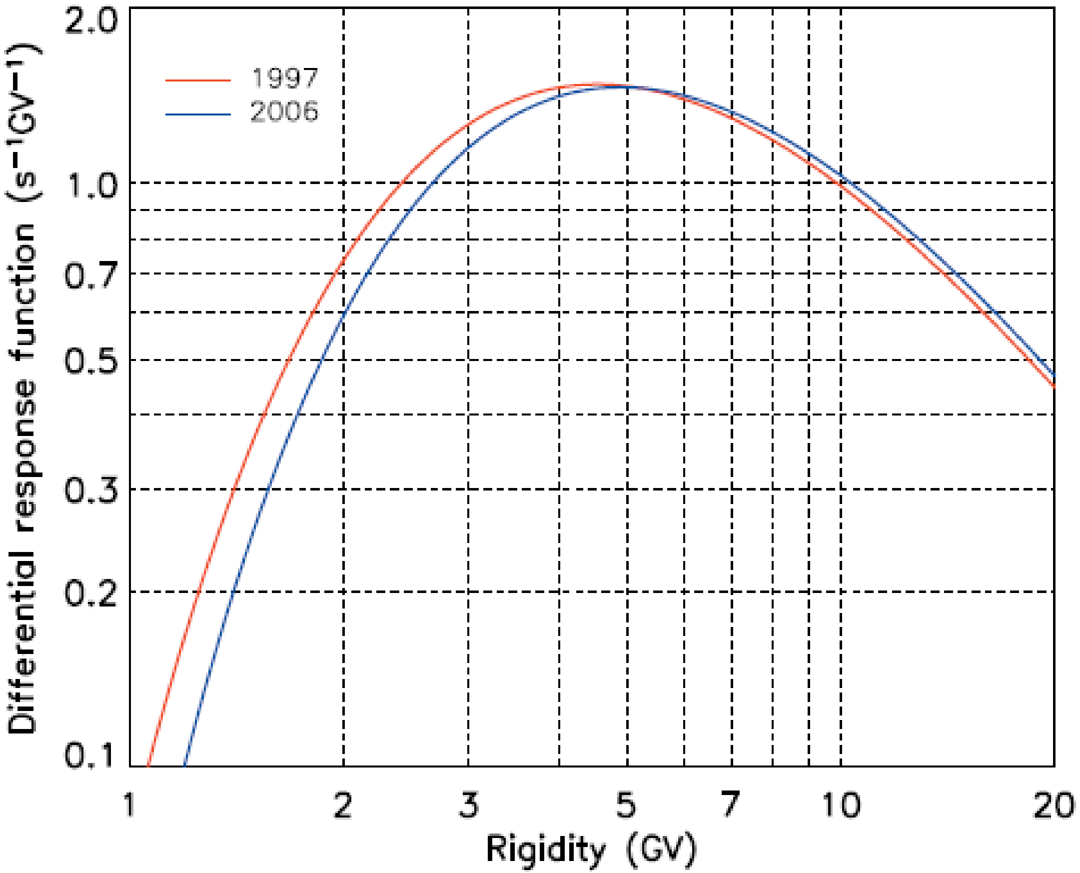
Cosmic Rays React to Heliospheric Magnetic Fields in Obvious Ways:

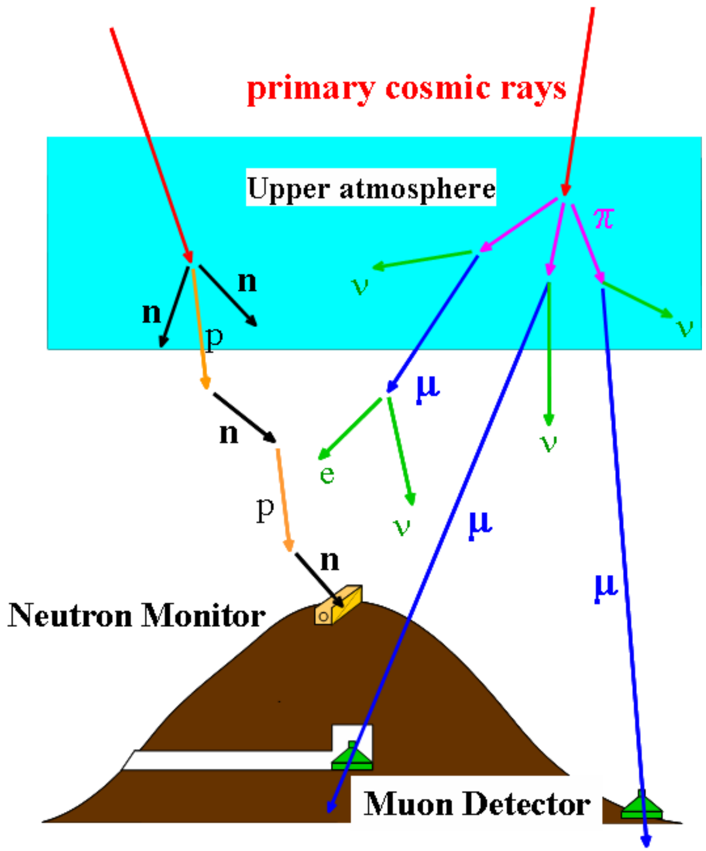


Cosmic Rays React to Heliospheric Magnetic Fields in Subtle Ways:



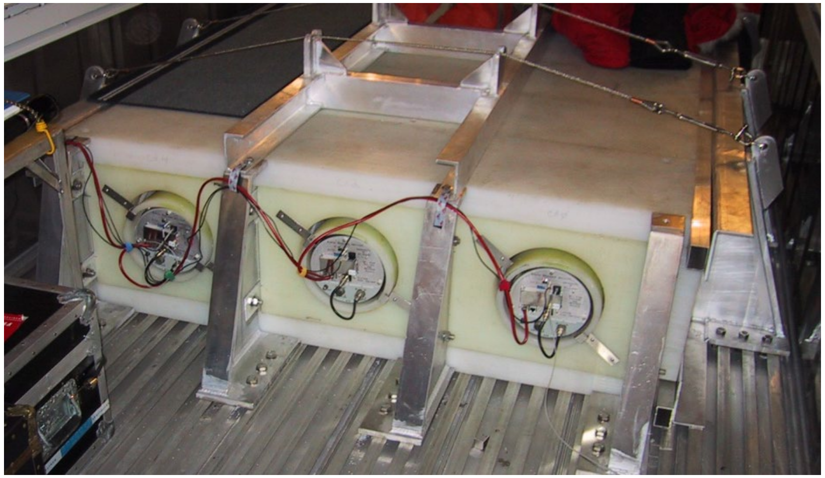
Alternating solar magnetic polarity creates this “crossover” in the spectrum at successive solar minima

GeV cosmic rays are rare!



- Observing them at high time resolution requires a large detector.
- Ground based instruments remain the state-of-the-art method for studying long term effects.
- Neutron monitors on the surface record the byproducts of nuclear interactions of high energy primary cosmic rays with Earth's atmosphere.

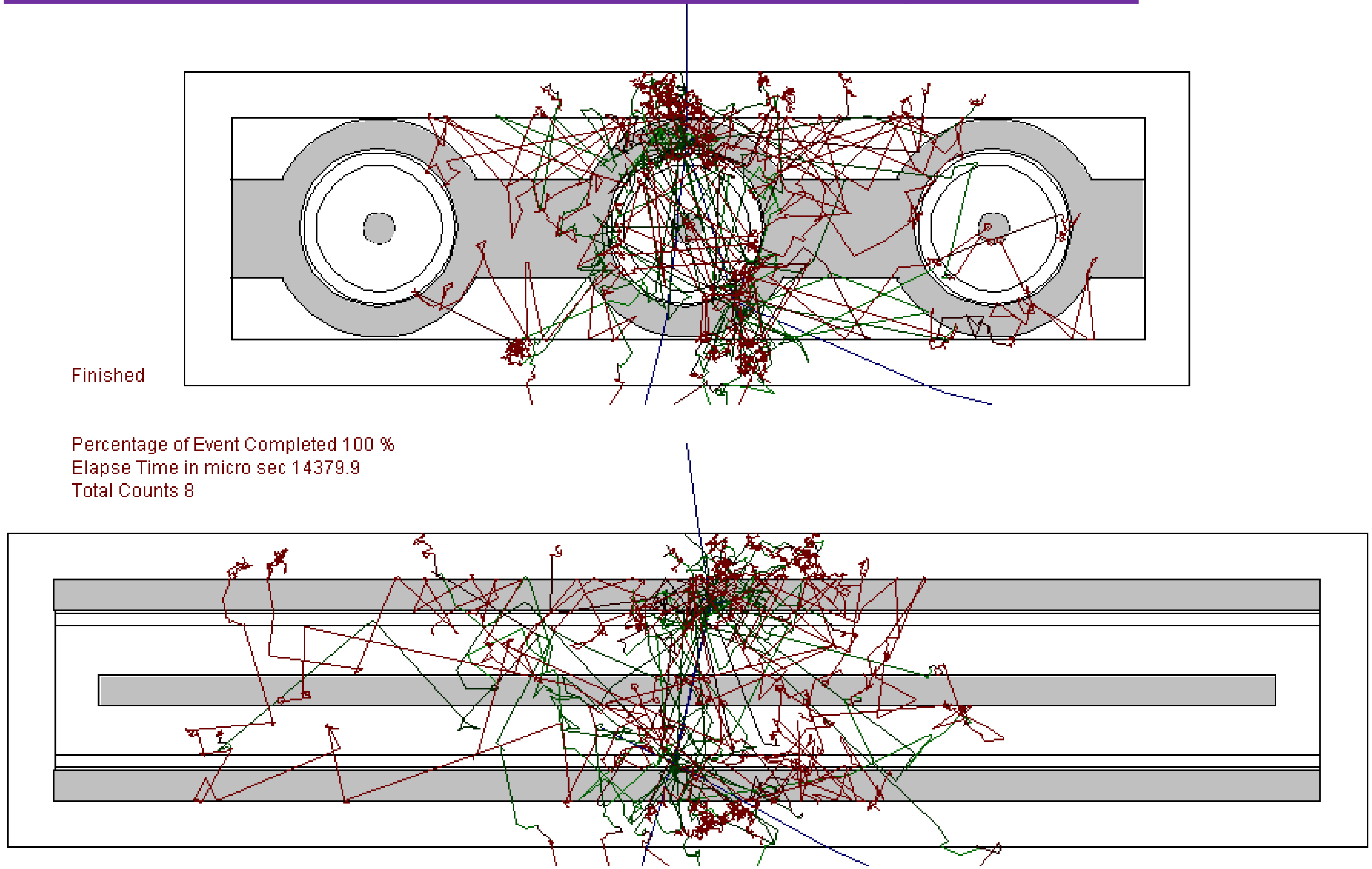
Neutron Monitor Principle



- An incoming hadron interacts with a nucleus of lead to produce several low energy neutrons.
- These neutrons thermalize in polyethylene or other material containing a lot of hydrogen.
- Thermal neutrons cause fission reaction in a ^{10}B (^{7}Li + ^{4}He) or ^{3}He (^{3}H + p) gas proportional counter.
- The large amount of energy released in the fission process dominates that of all penetrating charged particles. There is essentially no background.

Simulated Interaction In a Neutron Monitor

http://www.bartol.udel.edu/~clem/nm/display/intro.html



Energy Spectrum from Neutron Monitors

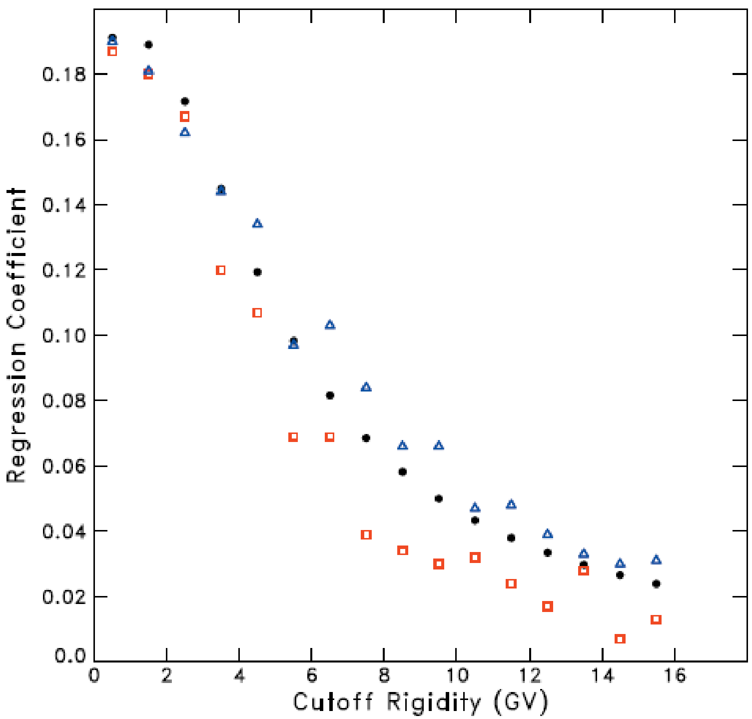
- Various Techniques Are Used
  - Different Geomagnetic Cutoff Rigidity
    - Latitude Surveys
    - Compare fixed monitors
  - Different Altitude at Similar Cutoff
  - Different Monitor Structure
  - Multiple neutrons from the same primary
    - Arrival time distribution
    - Time correlations among adjacent detectors
    - Patterns in adjacent detectors

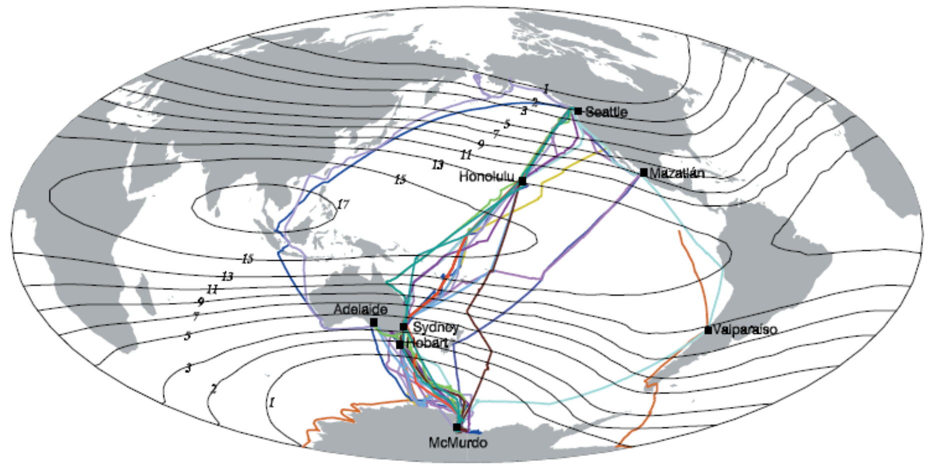
- Some examples follow, drawn mostly from work that I have been associated with. This is not a comprehensive review!

Geomagnetic Cutoff Rigidity

The oldest and most commonly applied technique relies on the geomagnetic cutoff. At any location on earth the magnetic field prevents cosmic rays below a specific cutoff rigidity from reaching the atmosphere. Cutoffs range from near zero to 18 GV.

Geomagnetic: Latitude Surveys



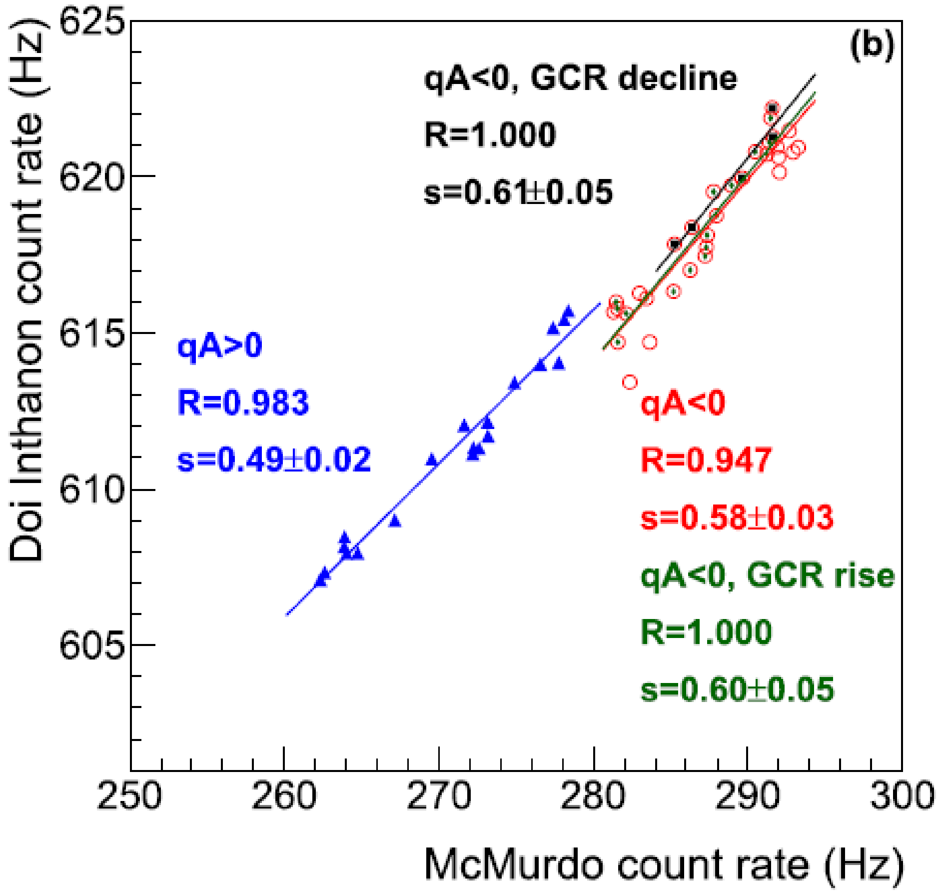


Regression analysis of a series of ship borne latitude surveys tracks the evolution of the spectral crossover in opposite solar magnetic polarity epochs.

Red squares, Negative polarity, **Blue triangles**: Positive polarity; **Black points**: Force field simulation (no polarity effect)

From: Nuntiyakul, W., P. Evenson, D. Ruffolo, A. Sáiz, J. Bieber, J. Clem, R. Pyle, M. L. Duldig, & J. E. Humble (2014), Latitude Survey Investigation Of Galactic Cosmic Ray Solar Modulation During 1994–2007. Astrophysical Journal, 795:11 (13pp), https://doi:10.1088/0004-637X/795/1/11

Geomagnetic: Fixed Stations



Solar polarity dependent regression effect seen in high (Doi Inthanon) and low (McMurdo) geomagnetic cutoff fixed neutron monitors

From: Mangeard, P.S., J. Clem, P. Evenson, R. Pyle, W. Mitthumsiri, D. Ruffolo , A. Sáiz & T. Nutaro (2018), Distinct Pattern of Solar Modulation of Galactic Cosmic Rays above a High Geomagnetic Cutoff Rigidity. The Astrophysical Journal, 858:43 (12pp), https://doi.org/10.3847/1538-4357/aabd3c

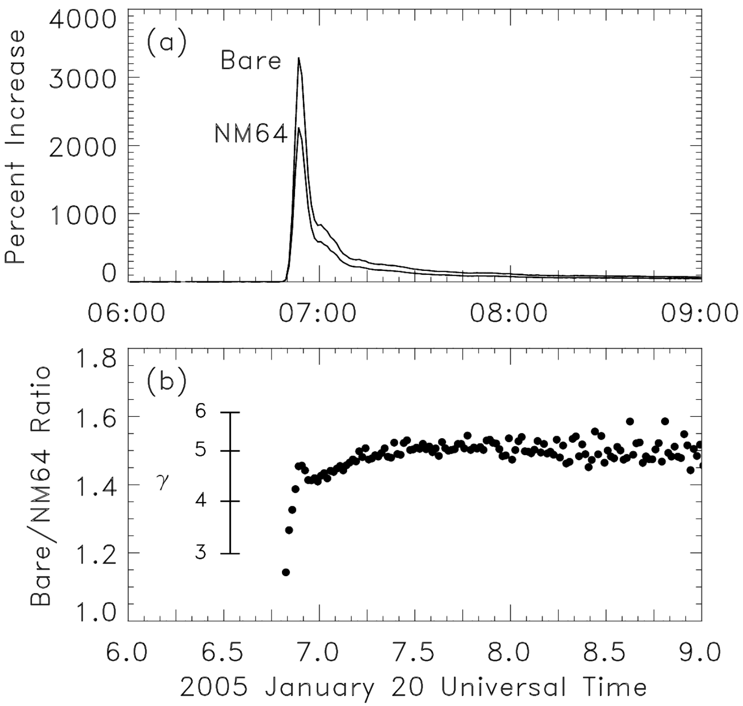
Different Altitude at Similar Cutoff

Secondaries from higher energy particle penetrate more deeply into the atmosphere.

Currently operating pairs:

- High Cutoff (shown)
  - Doi Inthanon - Chiang Mai
- Low Cutoff
  - Durham - Mt. Washington

Different Monitor Structure



South Pole station has both standard neutron monitor and an array of "bare" detectors lacking the lead producer.

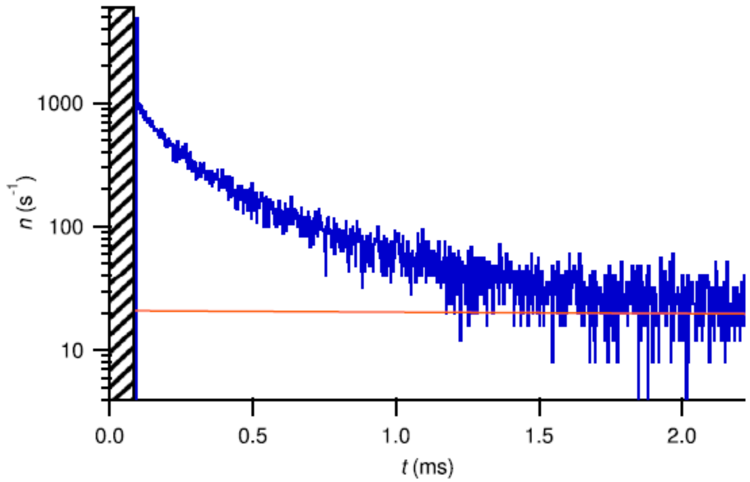
"Polar Bares" responds to lower particle energy on average.

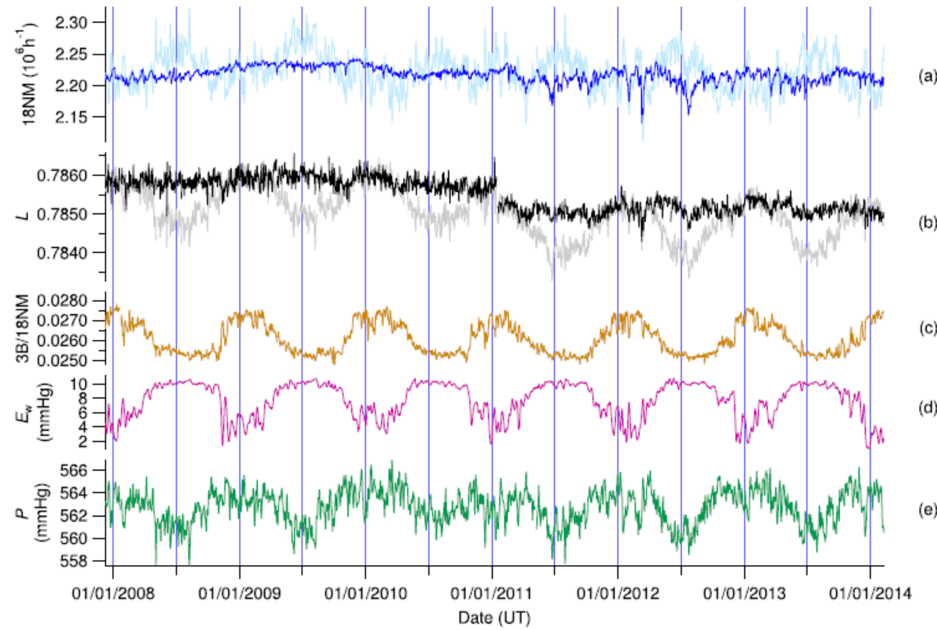
The Bare to NM64 ratio can be calibrated to give the spectral index of the primary particles.

This solar particle event shows a dispersive onset as the faster particles arrive first. The spectrum softens to ~ P^{-5} (where P is rigidity), which is fairly typical for GLE (Ground Level Enhancements). The dip around 06:55 UT is be related to a change in propagation conditions deduced from our transport model.

From: Bieber, J. W., Clem, J., Evenson, P., Pyle, R., Sáiz, A., & Ruffolo, D. (2013). Giant ground level enhancement of relativistic solar protons on 2005 January 20. I. Spaceship Earth Observations. Astrophysical Journal, 771, 92. https://doi.org/10.1088/0004-637X/771/2/92

Inherent Response to Multiple Neutrons from one Primary Particle: Timing

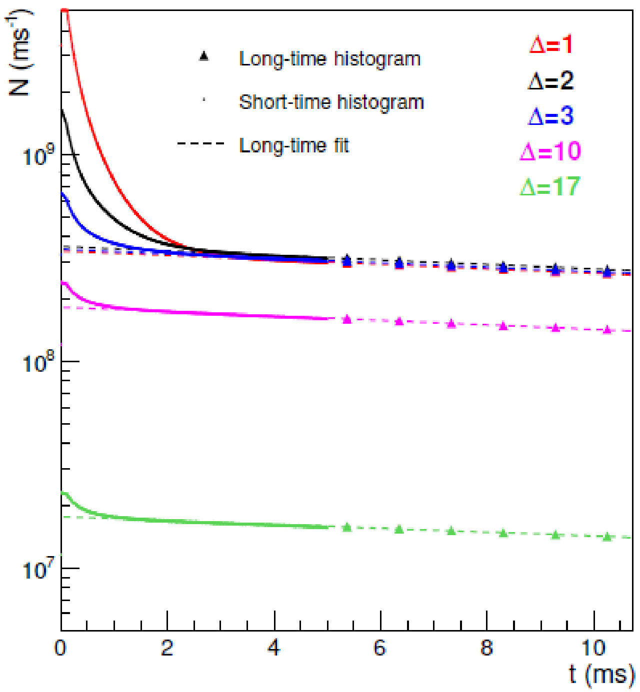




The distribution of intervals between successive neutron detections (right) can be calibrated to yield the spectral index of the cosmic rays (black trace, right).

From:Ruffolo, D., A. Sáiz, P.-S. Mangeard, N. Kamyan, P. Muangha, T. Nutaro, S. Sumran, C. Chaiwattana, N. Gasiprong, C. Channok, C. Wuttiya, M. Rujiwarodom, P. Tooprakai, B. Asavapibhop, J. W. Bieber, J. Clem, P. Evenson & K. Munakata (2016) Monitoring Short-Term Cosmic-Ray Spectral Variations Using Neutron Monitor Time-Delay Measurements. The Astrophysical Journal, 817:38 (12pp), https://doi:10.3847/0004-637X/817/1/38

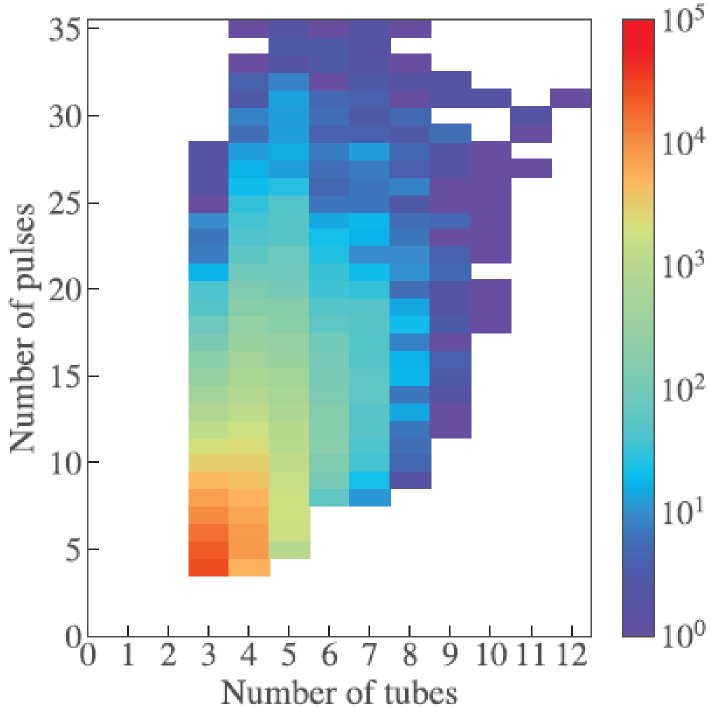
Inherent Response to Multiple Neutrons from one Primary Particle: Correlated Timing

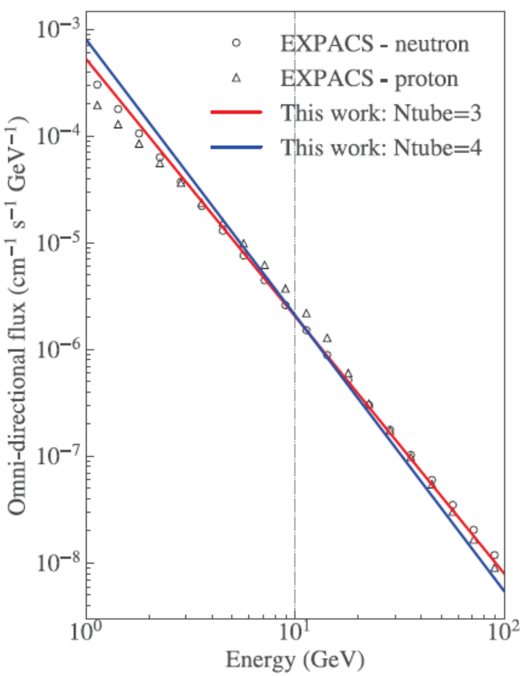


The rate at which the time correlation among nearby detectors degrades with distance is related to the spectrum of the cosmic rays.

From: Sáiz, A., W. Mitthumsiri, D.Ruffolo, P. Evenson & T. Nutaro (2017) Measurement of cross-counter leader fractions in an 18NM64: Detecting single and multiple atmospheric secondaries. PoS(ICRC2017)047.

Inherent Response to Multiple Neutrons from one Primary Particle: Interaction Patterns





The total number of neutrons detected and the number of adjacent detectors hit vary with incident energy. Their distribution (left) can be used to determine the particle spectrum (right)

From: Evenson, P., J. Clem, P.-S. Mangeard, W. Nuntiyakul, D. Ruffolo, A. Sáiz, A. Seripienlert & S. Seunarine (2021) Multiple Particle Detection in a Neutron Monitor, PoS(ICRC2021)1240.