Spaceship Earth:
NEUTRON MONITORS
IN THE 21ST CENTURY

Presentation to UARS Facilities Workshop

September 23, 2008

Paul Evenson and John W Bieber
University of Delaware
evenson@udel.edu
jwbieber@bartol.udel.edu

Neutron Monitor Website:
http://neutronm.bartol.udel.edu

Reference Document

- NEUTRON MONITORS IN THE 21ST CENTURY ?
  A report presented to the NRC Committee on Solar and Space Physics
  on the justification for neutron monitors and the status (as of April 2008)
  of the University of Delaware neutron monitor network.
- http://neutronm.bartol.udel.edu/cssp_report.pdf
- Update: Goose Bay has been closed and NSF support for McMurdo has been continued (Thanks!!)

WHAT IS A NEUTRON MONITOR ?

Neutron Monitor in Nain, Labrador
Construction completed November 2000

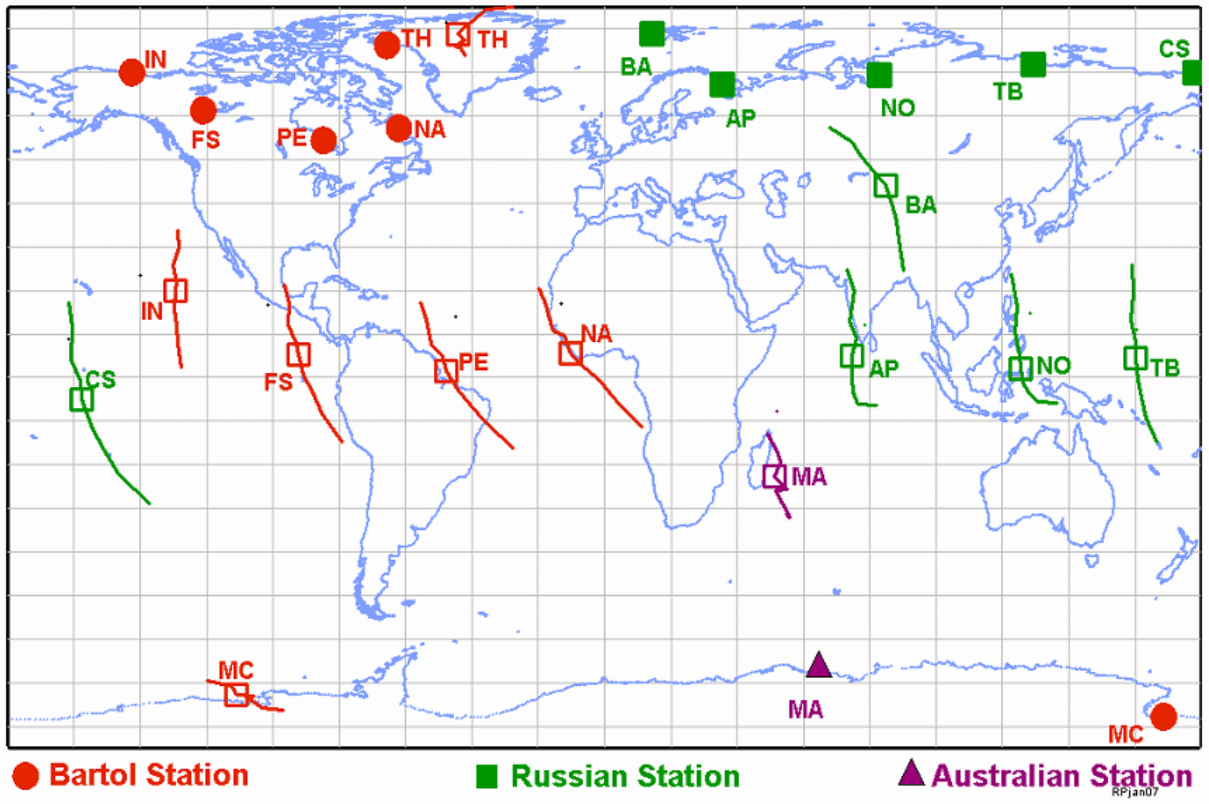
- A large instrument, weighing ~32 tons (standard 18-tube NM64)
- Detects secondary neutrons generated by collision of primary cosmic rays with air molecules
- Detection Method:
  - Older type – proportional counter filled with BF_3:
    $n + {}^{10}B \rightarrow \alpha + {}^{7}Li$
  - Modern type – counter filled with ${}^{3}He$:
    $n + {}^{3}He \rightarrow p + {}^{3}H$

SPACESHIP EARTH NEUTRON MONITOR ARRAY

- 12 Stations on 4 continents
- Multinational participation: USA, Russia, Australia, Canada
- Optimized to measure angular distribution of GeV solar cosmic rays
  - 9 stations view equatorial plane at 40-degree intervals
  - Thule, McMurdo, Barentsburg provide crucial 3-dimensional perspective

The Instrument is the *Array*

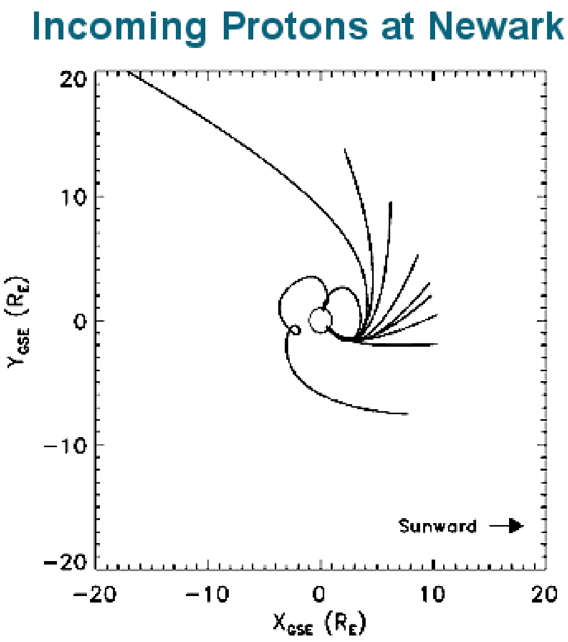
Below: Solid symbols denote station geographical locations. Average viewing directions (open squares) and range (lines) are separated from station locations because particles are deflected by Earth's magnetic field.



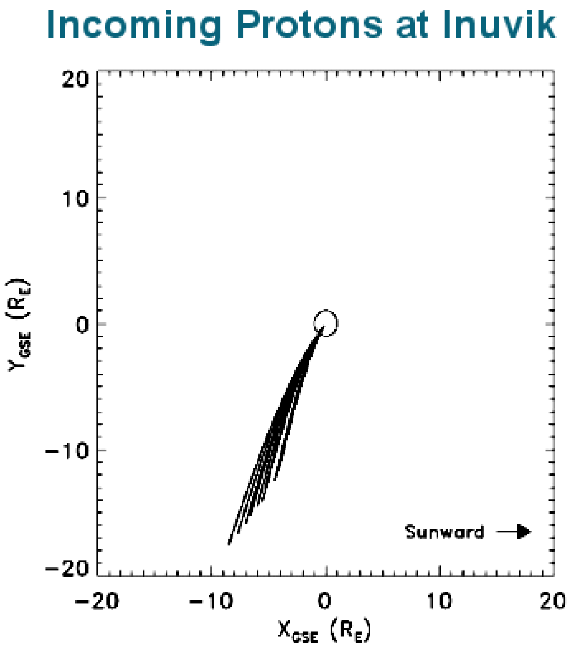
STATION CODES
IN: Inuvik, Canada
FS: Fort Smith, Canada
PE: Peawanuck, Canada
NA: Nain, Canada
BA: Barentsburg, Norway
MA: Mawson, Antarctica
AP: Apatity, Russia
NO: Norilsk, Russia
TB: Tixie Bay, Russia
CS: Cape Schmidt, Russia
TH: Thule, Greenland
MC: McMurdo, Antarctica

Why are all the stations at high latitude?
Prime Reason: Excellent directional sensitivity

Because of the combined effects of Earth's magnetic field and atmosphere, high latitude sites have superior directional sensitivity, relative to low latitude sites. The cosmic rays are "in focus."


Incoming Protons at Newark

Cosmic rays arriving at low and mid latitude stations (e.g., Newark, Delaware, above) arrive from widely dispersed directions. When the neutron monitor observes something, it can be difficult to determine the source direction.


Incoming Protons at Inuvik

Cosmic rays at high latitude sites (e.g., Inuvik, Canada, above) arrive from a narrow range of directions. The source direction is clear.

Trajectories are shown for vertically incident primaries corresponding to the 10-, 20-, … 90-percentile rigidities of a typical solar spectrum

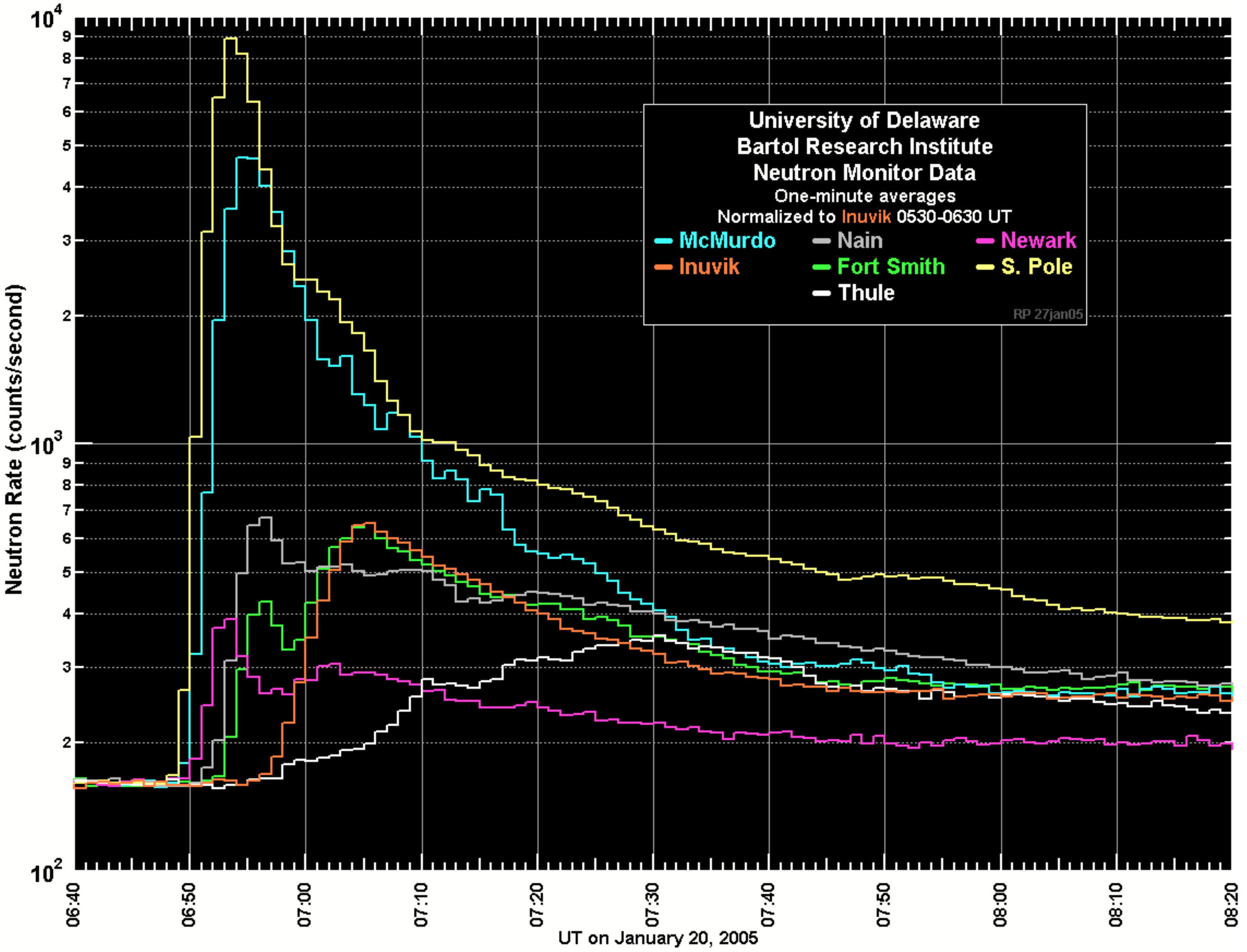
Spaceship Earth

EXPECTED SCIENCE OUTCOMES

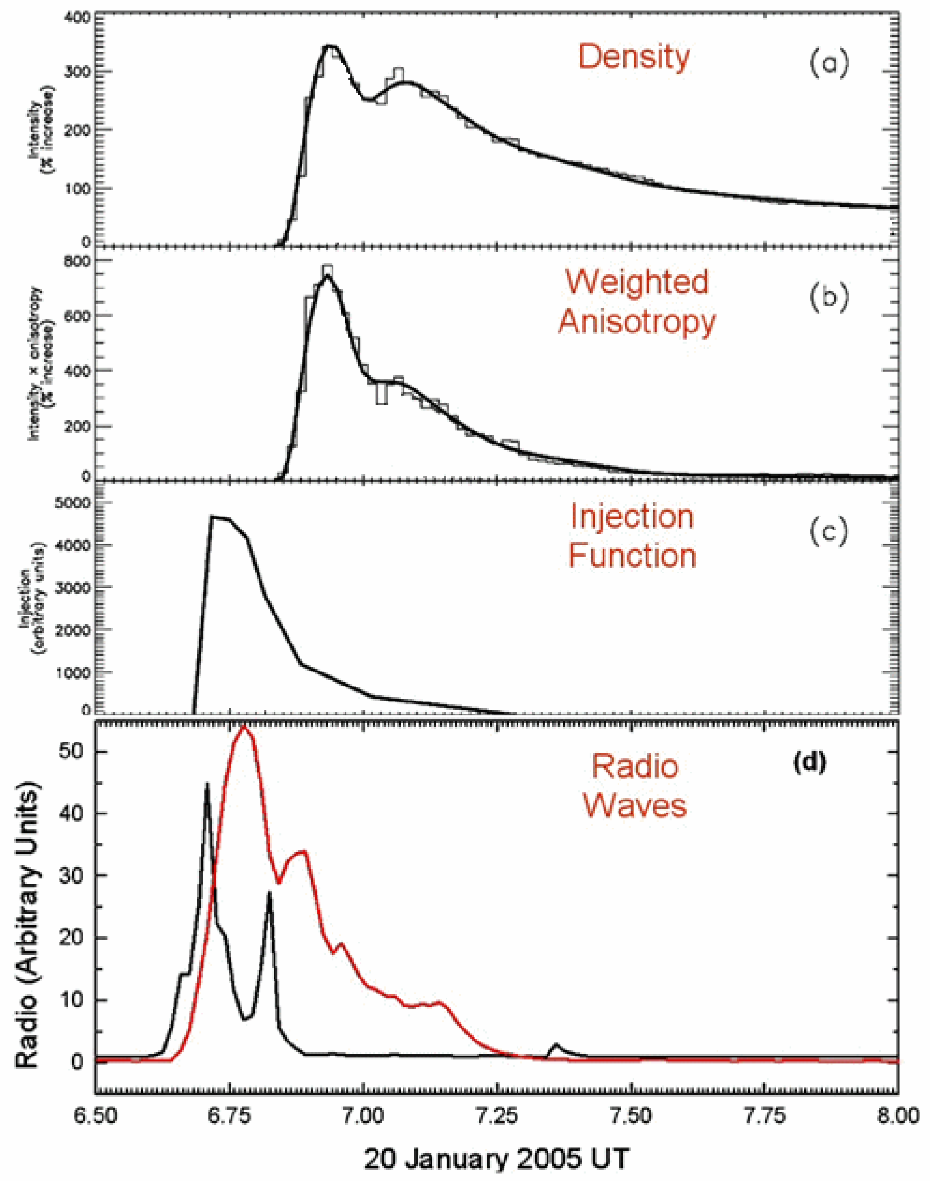
- Precise, high-time-resolution measurement of solar cosmic ray angular distribution
- Numerical modeling of interplanetary transport
  - Key source of information on the parallel mean free path
- Role of mirroring from structures in disturbed interplanetary medium
  - Magnetic bottleneck on flanks of ICME
  - Closed magnetic loop inside ICME
- Determination of injection profile at Sun, for comparison with radio and optical signatures
  - Relativistic solar cosmic rays present the clearest picture of the injection process because of their fast speed and large mean free path
- Earliest alert of a particle event, in case of a GLE
  - Precedes earliest GOES proton alert by ~10-30 minutes
  - ~40% of severe radiation storms are preceded by GLE

January 20, 2005 Ground Level Enhancement (GLE)

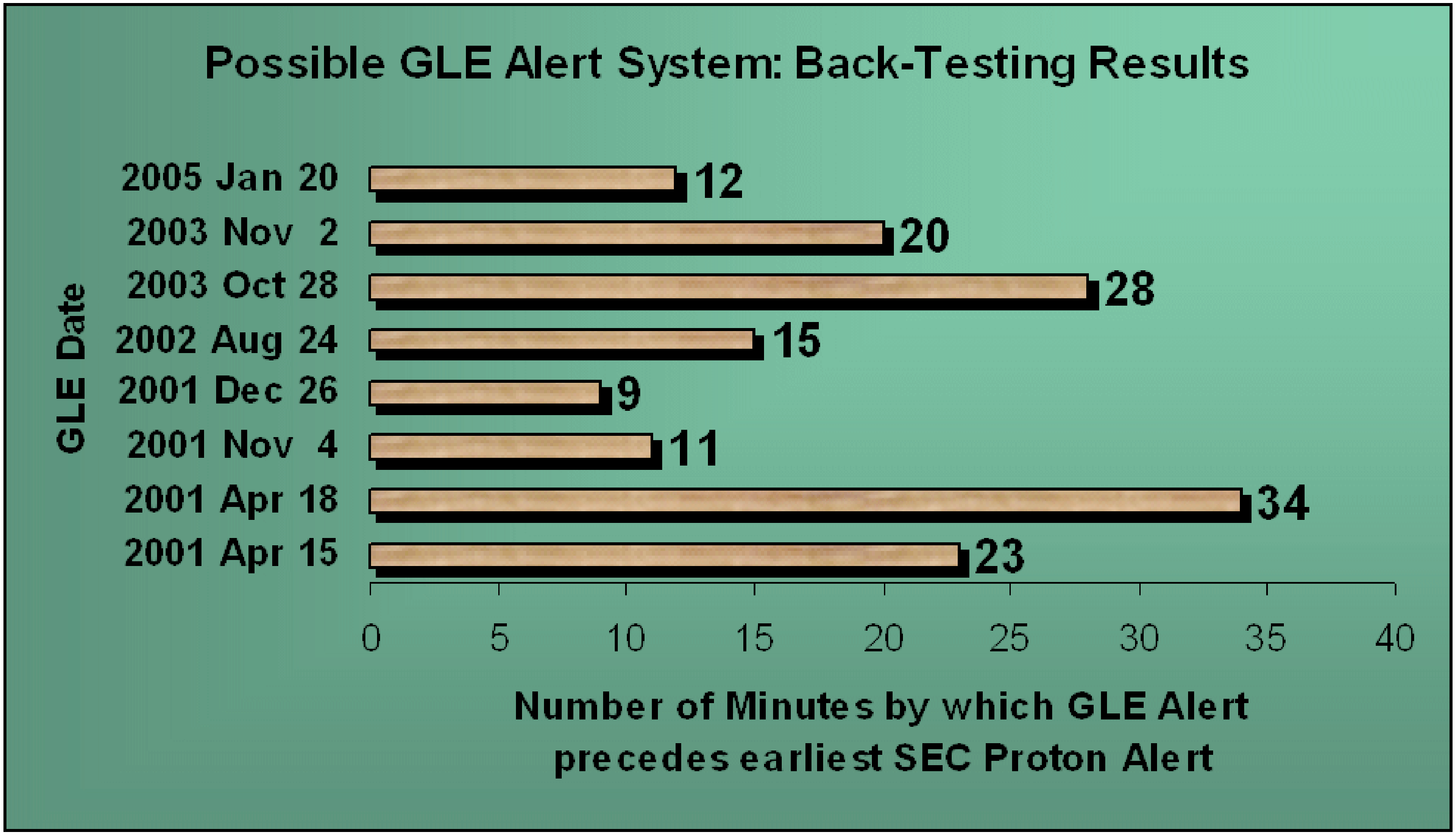
Largest Event since 1956 and Second Largest since Systematic Observations Began in 1936



Spaceship Earth Provides Key Information on Particle Acceleration at the Sun and Particle Transport in the Interplanetary Medium



- Shown at left, panels a-c, are observations (histograms) and modeling (curves) for the record-setting January 20, 2005 GLE
- Modeling solar particle transport is a key source of information about scattering of charged particles by magnetic turbulence
  - Here, the derived mean free path for GeV protons is ~0.8 AU
- Owing to their fast speed and long mean free path, GLE particles provide the clearest picture of injection onto the Sun-Earth field line (panel c)
  - Comparison with solar optical and radio signatures provides insight into acceleration mechanisms – At left, note similarity between injection function and 500 MHz radio waves (red curve in panel d)

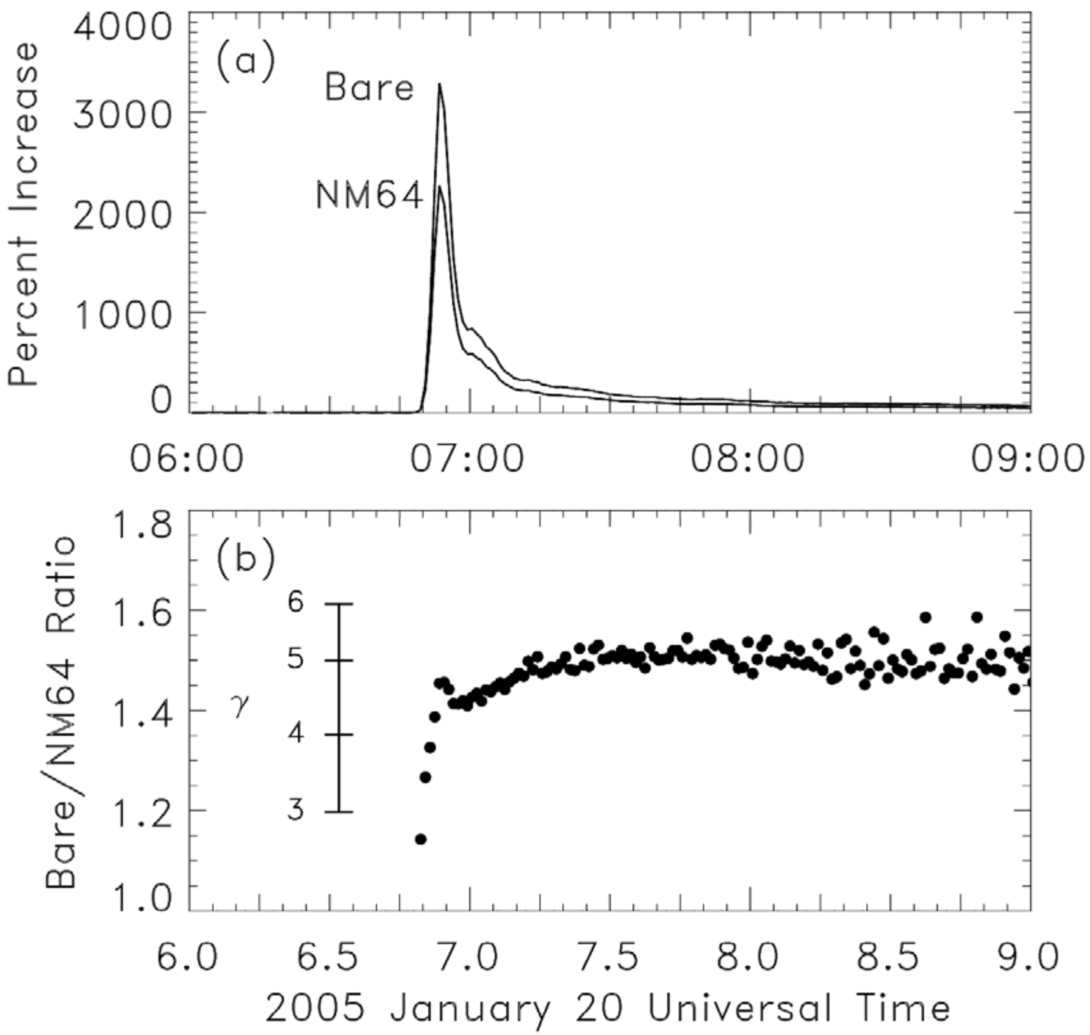


- In this study, a GLE alert is issued when 3 stations of *Spaceship Earth* (plus South Pole) record a 4% increase in 3-min averaged data
- With 3 stations, false alarm rate is near zero
- GLE Alert precedes SEC Proton Alert by ~ 10-30 min
- For details, see Kuwabara et al., *Space Weather*, **4**, S10001, 2006.

HIGH-ALTITUDE NEUTRON MONITORS: POTENTIAL SCIENCE OUTCOMES

- Galactic cosmic ray spectrum (steady-state and transient events) from network observations
- Solar cosmic ray spectrum from high-altitude polar observatory (NM64/Bare)
  - Possible space weather applications if ~GeV spectrum is predictive of lower energies
- Relativistic solar neutrons from high-altitude equatorial monitors
- Source of long-term decline in South Pole neutron rate
  - Do other high-altitude polar sites see the same effect ?

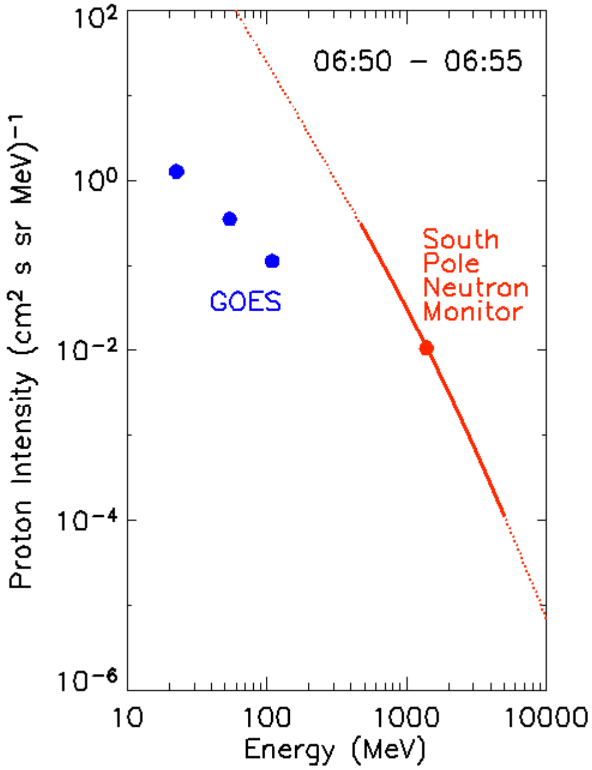
ENERGY SPECTRUM: POLAR BARE METHOD

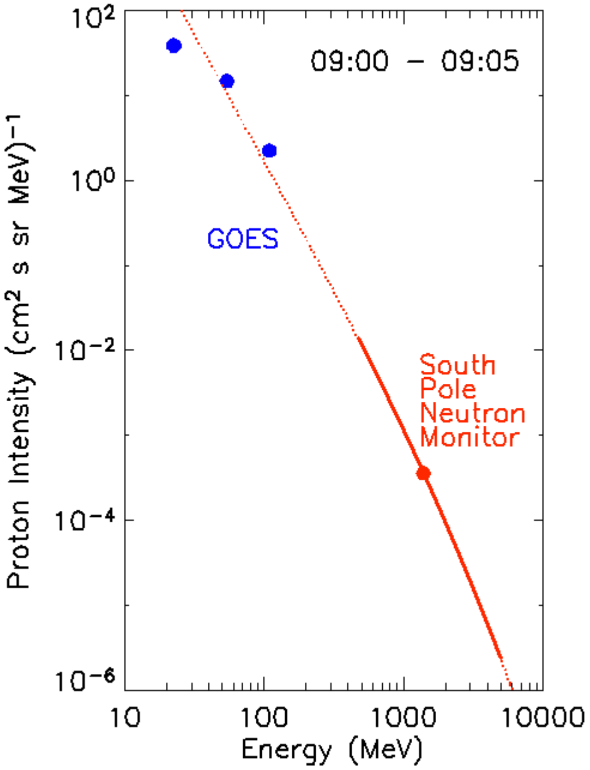


South Pole station had both a standard neutron monitor (NM64) and a monitor lacking the usual lead shielding (Bare). The Polar Bare responds to lower particle energy on average. Comparison of the Bare to NM64 ratio provides information on the particle spectrum.

- This event displays a beautiful dispersive onset (lower panel), as the faster particles arrive first.
- Later, the rigidity spectrum softens to ~P^{-5} (where P is rigidity), which is fairly typical for GLE.

POLAR BARE METHOD PERMITS DETERMINATION OF ABSOLUTE SPECTRUM (AMPLITUDE AS WELL AS INDEX)





- Left-hand plot is during neutron monitor peak – Velocity dispersion is much in evidence as the lower energies “catch up”
- Right-hand plot is during event decay; South Pole spectrum extrapolates reasonably well to GOES
- There is some indication that the initial GLE spectrum is predictive of the GOES spectrum ~1-2 hr later. This could be useful for near-term forecasts of space radiation hazard, but further study is needed.

Why Has NSF Decided to Withdraw Support for Neutron Monitors ?

- NOT because of bad peer reviews
- NOT because of lack of community support
- But there seems to be a problem with "Long-Term Measurements"

Excerpts at right are from NSF's response to our request for reconsideration of the original declination decision. The response was over the signatures of Scott Borg and Richard Behnke

- "… the external reviewers were very supportive of your proposed work. However, external reviewer input is advisory to NSF and it constitutes only one of several factors that must be weighed by program officers in developing an overall recommendation."
- "With regard to impact on the community - we acknowledge that withholding NSF support through this declination will adversely impact those researchers who have relied on the data from this network in the past."
- "… a very important question that has not been addressed is; to what extent should NSF continue support of long term measurements because of a perceived importance of longevity of measurements for its own sake? NSF is not a traditional mission agency and if NSF invests in long term observations for specific research purposes then there must be the possibility of NSF stopping support at some point."

Neutron Monitors in the 21st Century?

Nine Reasons Why the Answer is “Yes!” (# 1-5)

1. Neutron monitor arrays are the state-of-the-art method for observing GeV cosmic rays.
   - ***Nothing flown in space is competitive in this energy range***.
2. Modeling interplanetary transport of solar cosmic rays provides key information on how charged particles are scattered by magnetic turbulence (parallel mean free path).
3. GLE particles provide the clearest picture of the particle injection at the Sun (injection onset and time profile).
4. Modeling GLE provides insight into the role of magnetic mirroring in cosmic ray transport.
5. Neutron monitors can provide first alert of some major proton events (with existing sensitivity, ~40% of severe radiation storms).

Neutron Monitors in the 21st Century?

Nine Reasons Why the Answer is “Yes!” (# 6-9)

6. High-altitude equatorial monitors sometimes observe direct relativistic solar neutrons, an important window into the acceleration site, because neutrons travel unimpeded by the magnetic field.
7. High-altitude polar monitor combined with “bare counter” provides clean measurement of relativistic solar particle spectrum.
   - Possible space weather applications if the relativistic spectrum is predictive of lower energies.
8. The cause of the long-term decline in the South Pole neutron rate should be identified.
9. Neutron monitors provide unique insight into 22-yr (magnetic cycle) variations of the solar modulation of cosmic rays.

Selected Publications by Our Group

Total number of publications acknowledging our last two NSF grants, ATM-0000315 (2000-2005) or ATM-052787(2005-2007) is 54. We include only a sampling here, concentrated on those with an observational focus. Some of these articles can be downloaded from http://neutronm.bartol.udel.edu/reprints/main.html

- "Energetic Particle Observations During the 2000 July 14 Solar Event," J. W. Bieber, W. Droege, P. Evenson, R. Pyle, D. Ruffolo, U. Pinsook, P. Tooprakai, M. Rujiwarodom, T. Khumlumlert, and S. Krucker, *Astrophys. J.,* **567**, 622-634, 2002.
- "Cosmic Ray Spectra and the Solar Magnetic Polarity: Preliminary Results from 1994–2002," J. W. Bieber, J. Clem, M. L. Duldig, P. Evenson, J. E. Humble, and R. Pyle, *Solar Wind Ten*, AIP Conf. Proc. 679, edited by M. Velli, R. Bruno, and F. Malara, pp. 628-631, 2003.
- "Loss Cone Precursors to Forbush Decreases and Advance Warning of Space Weather Effects," K. Leerungnavarat, D. Ruffolo, and J. W. Bieber, *Astrophys. J.*, **593**, 587-596, 2003.
- "Cosmic ray anisotropy before and during the passage of major solar wind disturbances," A. V. Belov, J. W. Bieber, E. A. Eroshenko, P. Evenson, R. Pyle, and V. G. Yanke, *Adv. Space Res.,* **31**, 919-924, 2003.
- "Spaceship Earth Observations of the Easter 2001 Solar Particle Event," J. W. Bieber, P. Evenson, W. Dröge, R. Pyle, D. Ruffolo, M. Rujiwarodom, P. Tooprakai, and T. Khumlumlert, *Astrophys. J. (Lett.)*, **601**, L103-L106, 2004.
- "Geometry of an Interplanetary CME on October 29, 2003 Deduced from Cosmic Rays," T. Kuwabara, and 18 co-authors, *Geophys. Res. Lett.*, **31**, L19803, doi:10.1029/2004GL020803, 2004.
- "Latitude Survey Observations of Neutron Monitor Multiplicity," J. W. Bieber, J. M. Clem, M. Duldig, P. A. Evenson, J. E. Humble, K. R. Pyle, *J. Geophys. Res.*, **109**, A12106, doi:10.1029/2004JA010493, 2004.
- "A 'Loss-Cone' Precursor of an Approaching Shock Observed by a Cosmic-Ray Muon Hodoscope on October 28, 2003," K. Munakata, and 11 co-authors, *Geophys. Res. Lett.*, **32**, L03S04, doi:10.1029/2004GL021469, 2005.
- "Relativistic Solar Neutrons and Protons on 28 October 2003," J. W. Bieber, J. Clem, P. Evenson, R. Pyle, D. Ruffolo, and A. Sáiz, *Geophys. Res. Lett.*, **32**, L03S02, doi:10.1029/2004GL021492, 2005.
- "Addressing solar modulation and long-term uncertainties in scaling secondary cosmic rays for in situ cosmogenic nuclide applications," N. A. Lifton, J. W. Bieber, J. M. Clem, M. L. Duldig, P. Evenson, J. E. Humble, and R. Pyle, *Earth Planet. Sci. Lett.*, **239**, 140-161, doi:10.1016/j.epsl.2005.07.001, 2005.
- "Largest GLE in Half a Century: Neutron Monitor Observations of the January 20, 2005 Event," J. W. Bieber, J. Clem, P. Evenson, R. Pyle, M. Duldig, J. Humble, D. Ruffolo, M. Rujiwarodom, and A. Sáiz, *Proc. 29th Internat. Cosmic Ray Conf.* (Pune), **1**, 237-240, 2005.
- "Neutron Monitor Temperature Coefficients: Measurements for BF_3 and ^3He Counter Tubes," P. Evenson, J. W. Bieber, J. Clem and R. Pyle, *Proc. 29th Internat. Cosmic Ray Conf.* (Pune), **2**, 485-488, 2005.
- "On the Cross-Field Diffusion of Galactic Cosmic Rays into an ICME," K. Munakata, S. Yasue, C. Kato, J. Kóta, M. Tokumaru, M. Kojima, A. A. Darwish, T. Kuwabara, and J. W. Bieber, *Adv. Geosci.*, **2**, 115-124, 2006.
- "Real-Time Cosmic Ray Monitoring System for Space Weather," T. Kuwabara, and 16 co-authors, *Space Weather*, **4**, S08001, doi:10.1029/2005SW000204, 2006.
- "Development of a GLE Alarm System Based Upon Neutron Monitors," T. Kuwabara, J. W. Bieber, J. Clem, P. Evenson, and R. Pyle, *Space Weather*, **4**, S10001, doi:10.1029/2006SW000223, 2006.
- "High-Energy Protons Associated with Liftoff of a Coronal Mass Ejection," Kocharov, L., O. Saloniemi, J. Torsti, E. Riihonen, J. Lehti, K.-L. Klein, L. Didkovsky, D. L. Judge, A. R. Jones, and R. Pyle, *Astrophys. J.*, **659**, 780-787, 2007.
- "Long-Term Decline of South Pole Neutron Rate," J. W. Bieber, J. Clem, D. Desilets, P. Evenson, D. Lal, C. Lopate, and R. Pyle, *J. Geophys. Res.*, in press, 2007.

Why a Facility --Selected Publications by Other Groups Using UD Neutron Monitor Data

This is not a comprehensive list. We include selected publications by external groups to demonstrate that our data are used broadly in the research community.

- "A Detailed Comparison of Cosmic Ray Gaps with Solar Gnevyshev Gaps," R. P. Kane, *Solar Physics*, **236**, 207-226, 2006.
- "Magnetospheric effects in cosmic rays during the unique magnetic storm on November 2003," A. Belov, L. Baisultanova, E. Eroshenko, H. Mavromichalaki, V. Yanke, V. Pchelkin, C. Plainaki, and G. Mariatos, *J. Geophys. Res.*, **110**, A09S20, doi:10.1029/2005JA011067, 2005.
- "Relativistic nucleon and electron production in the 2003 October 28 solar event," L. I. Miroshnichenko, K.-L. Klein, G. Trottet, P. Lantos, E. V. Vashenyuk, Y. V. Balabin, and B. B. Gvozdevsky, *J. Geophys. Res.*, **110**, A09S08, doi:10.10292004JA010936, 2005.
- "Radiation dose along North American transcontinental flight paths during quiescent and disturbed geomagnetic conditions," I. Getley, M. Duldig, D. Smart, and M. Shea, *Space Weather,* **3**, S01004, doi:10.1029/2004SW000110, 2005.
- "Ground Level Muons Coincident with the 20 January 2005 Solar Flare," C. D'Andrea and J. Poirier, *Geophysical Research Letters,* **32**, L14102, doi:10.1029/2005GL023336, 2005.
- "Cosmic-Ray Variations During the Two Greatest Bursts of Solar Activity in the 23rd Solar Cycle," E. Eroshenko, A. Belov, H. Mavromichalaki, G. Mariatos, V. Oleneva, C. Plainaki, and V. Yanke, *Solar Physics*, **224**, 345-358, 2004.
- "Energetic Particles and Corotating Interaction Regions in the Solar Wind," I. G. Richardson, *Space Science Reviews*, **111**, 267-376, 2004.
- "Interplanetary and Solar Plasma Parameters of the 14 July 2000 Ground Level Enhancement," S. S. Al-Thoyaib, *International Journal of Modern Physics D*, **12**, 337-344, doi:10.1142/S0218271803002275, 2003.
- "Latitudinal and radial variation of >2 GeV/n protons and alpha-particles at solar maximum: ULYSSES COSPIN/KET and neutron monitor network observations," A. V. Belov, E. A. Eroshenko, B. Heber, V. G. Yanke, A. Raviart, R Müller-Mellin, and H. Kunow, *Annales Geophysicae*, **21**, 1295-1302, 2003.
- "Ground level muons in coincidence with the solar flare of 15 April 2001," J. Poirier and C. D'Andrea, *Journal of Geophysical Research*, **107**, SSH 14-1, doi:10.1029/2001JA009187, 2002.
- "Influence of Variations of the Cosmic Rays on Atmospheric Pressure and Temperature in the Southern Geomagnetic Pole Region," L. V. Egorova, V.Ya. Vovk, and O. A. Troshichev, *Journal of Atmospheric and Solar-Terrestrial Physics,* **62**, 955-966, 2000.