High Energy Solar Neutrons and How to Measure Them

Andrew Kuhlman[1], James Ryan[1]

[1]University of New Hampshire

Neutron Monitors

Neutron monitors are ground-based particle detectors that are sensitive to nucleons from cosmic ray showers [1].

When a cosmic ray particle strikes molecules in the atmosphere, it can create secondary particles which can, in turn, create secondary particles of their own. This cascade of particles is known as a cosmic ray shower (figure 1 left).

A neutron monitor consists of several components (figure 1 right). The polyethylene reflector helps prevent background nucleons from the environment from entering the detector. The lead producer and polyethylene moderator increase the chances of detection. Finally, the proportional counter tube "counts" the neutrons that enter it.

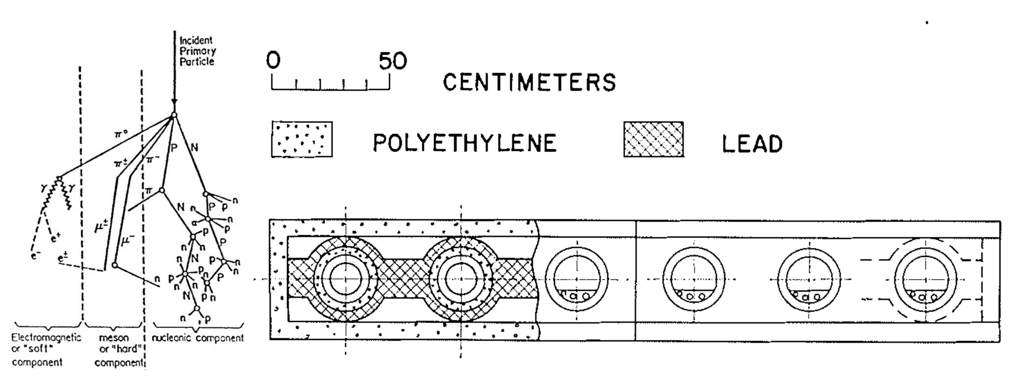

Figure 1. Left – the particles produced in a cosmic ray shower [1]. Right – the components of a neutron monitor [2].

Neutron Monitor Network

The global neutron monitor network consists of ~50 stations distributed around the globe (figure 2).

Because of the shielding of charged particles by the Earth's magnetic field, which varies significantly with geomagnetic latitude and incoming particle direction, each neutron monitor is sensitive to different parts of the cosmic ray spectrum. Because of this, the global neutron monitor network acts as a giant spectrometer [3]. Stations at higher latitudes are more sensitive to charged radiation.

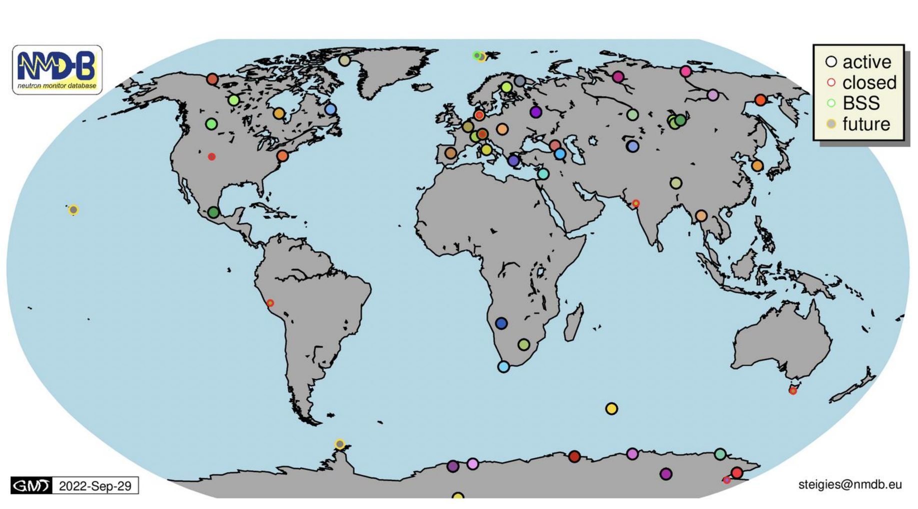

Figure 2. The global neutron monitor network. Image from www.nmdb.eu

What Are Solar Neutrons?

If neutrons from solar flares are high enough in energy (> ~250-300 MeV), they will cause particle showers in the Earth's atmosphere that can be detected on the ground [4].

During solar flares, high energy neutrons are produced by accelerated ions in the solar atmosphere. These neutrons carry information about solar energetic particle acceleration and nuclear reactions happening in the solar atmosphere [5]. Sometimes, these neutrons cause signals that can be detected at ground level, as shown in figure 3.

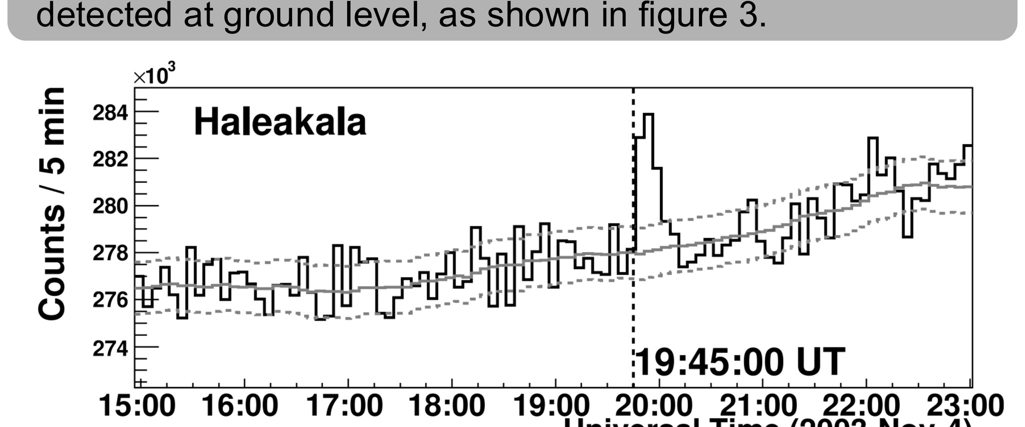

Figure 3. A solar neutron event measured by the Haleakalā neutron monitor in 2003. [13]

Not All Neutron Monitors are Created Equal

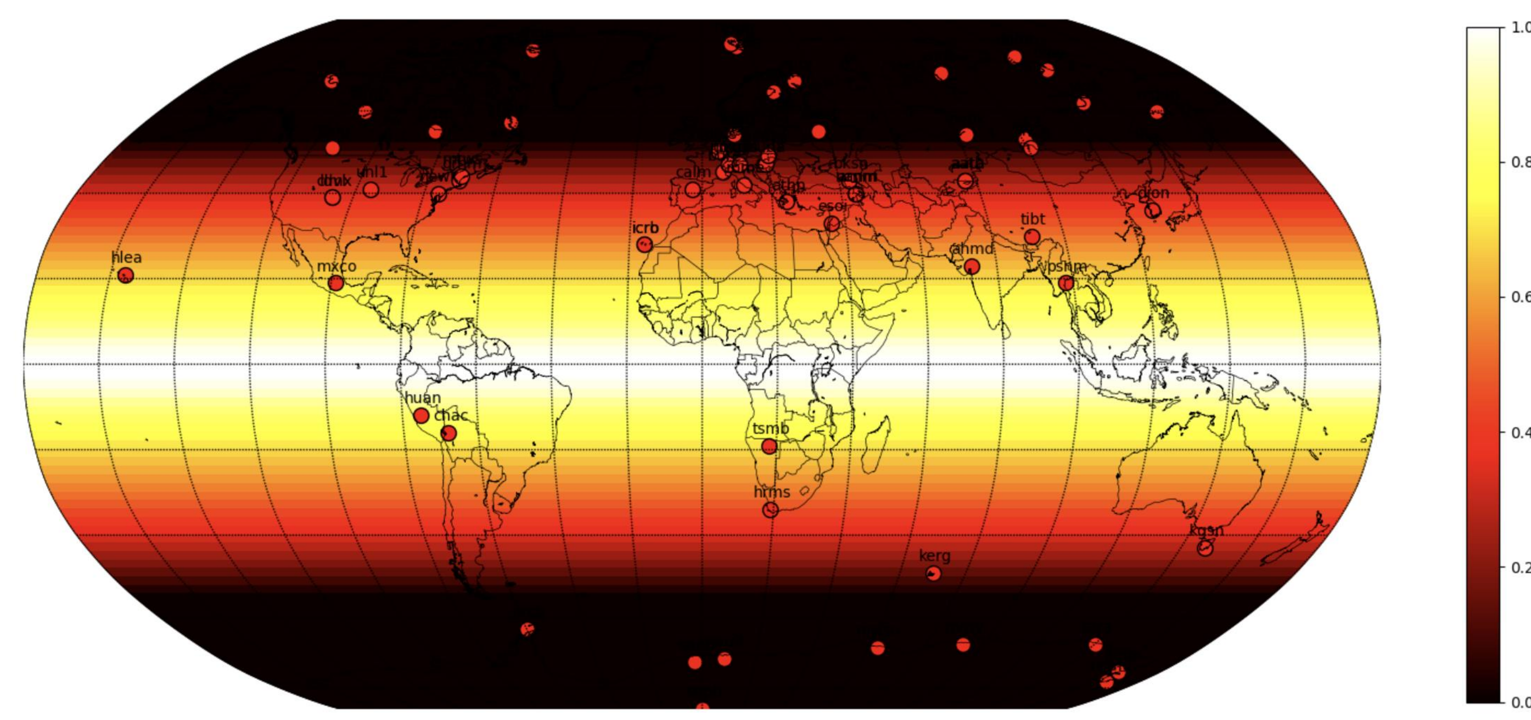

Figure 4. The relative sensitivity of neutron monitor stations to solar neutrons. Stations which are closer to the equator are better positions to detect solar neutrons.

Not all neutron monitor stations are equally sensitive to solar neutron events. A station's sensitivity depends on:

- **The detector's location.** A station at low latitude is ideal (See figure 4). Since solar neutrons are not affected by magnetic fields, the response of the detector to solar neutrons is dependent on the solar zenith angle, where an angle closer to vertical is more preferred. This means a tropical location, like that of the Haleakalā monitor in Hawai'i, is a great boon for solar neutron detection [6].
- **The local time and season at the detector.** Local noon around the summer solstice is the most ideal time for solar neutron detection for most monitors (See figure 6). As discussed in the foregoing bullet point, the chances of detection are highest when the sun is directly overhead. For example, the Jungfraujoch neutron monitor in Switzerland, typically poorly located for solar neutrons was able to detect a solar neutron event on June 3, 1982 because it was near local noon, near the summer solstice [7].
- **The detector's altitude.** A station at high altitude is also advantageous for solar neutron detection. The atmosphere attenuates solar neutrons, so the number of observed neutrons increases exponentially with altitude [6].

Neutron Producing Flares

The plot shown in figure 5 is from the first confirmed solar neutron event on June 3, 1982 and is characteristic of events that result in detection on the ground [7].

The first peak (figure 5 middle, 11:43) is called the "impulsive phase" and due to photons. The second peak (11:45) is called the "extended phase", has a significant neutron component, and can last for many minutes to hours [7] [8] [9]. The extended phase is also rich in pion decay radiation, unlike the impulsive phase [10]. Lower energy radiation (figure 5 top), such as x-ray and MeV gammas, returns to pre-flare levels (or significantly decreases) during the extended phase, unlike the higher energy radiation. The Jungfraujoch neutron monitor (figure 5 bottom) began detecting a neutron monitor event at ~11:45 which lasted until at least 11:55.

Best Locations for New Stations

New neutron monitors in Africa, South Asia, Southeast Asia, Oceania, and/or South America would dramatically improve the potential of the neutron monitor network to detect solar neutrons.

As shown in Figure 4, there is currently a dearth of monitors near the equator, the latitude range with the best chance at detection

Why Do We Care?

Because the interplanetary and geomagnetic fields only affect charged particles, neutrons, along with gamma rays, provide direct information about flare regions [11].

The energy spectrum of neutrons released from the sun is highly dependent on the spectrum of ions accelerated in the flares. Improved estimates of the solar neutron energy spectrum help us glean insight into the total number, energy spectrum, time dependence, and angular distribution of ions accelerated in flares. They also provide information on composition, scale height, and magnetohydrodynamic turbulence in the flare region [12].

Acknowledgements

This work has been supported by NSF grants 2112441 and 2149811.

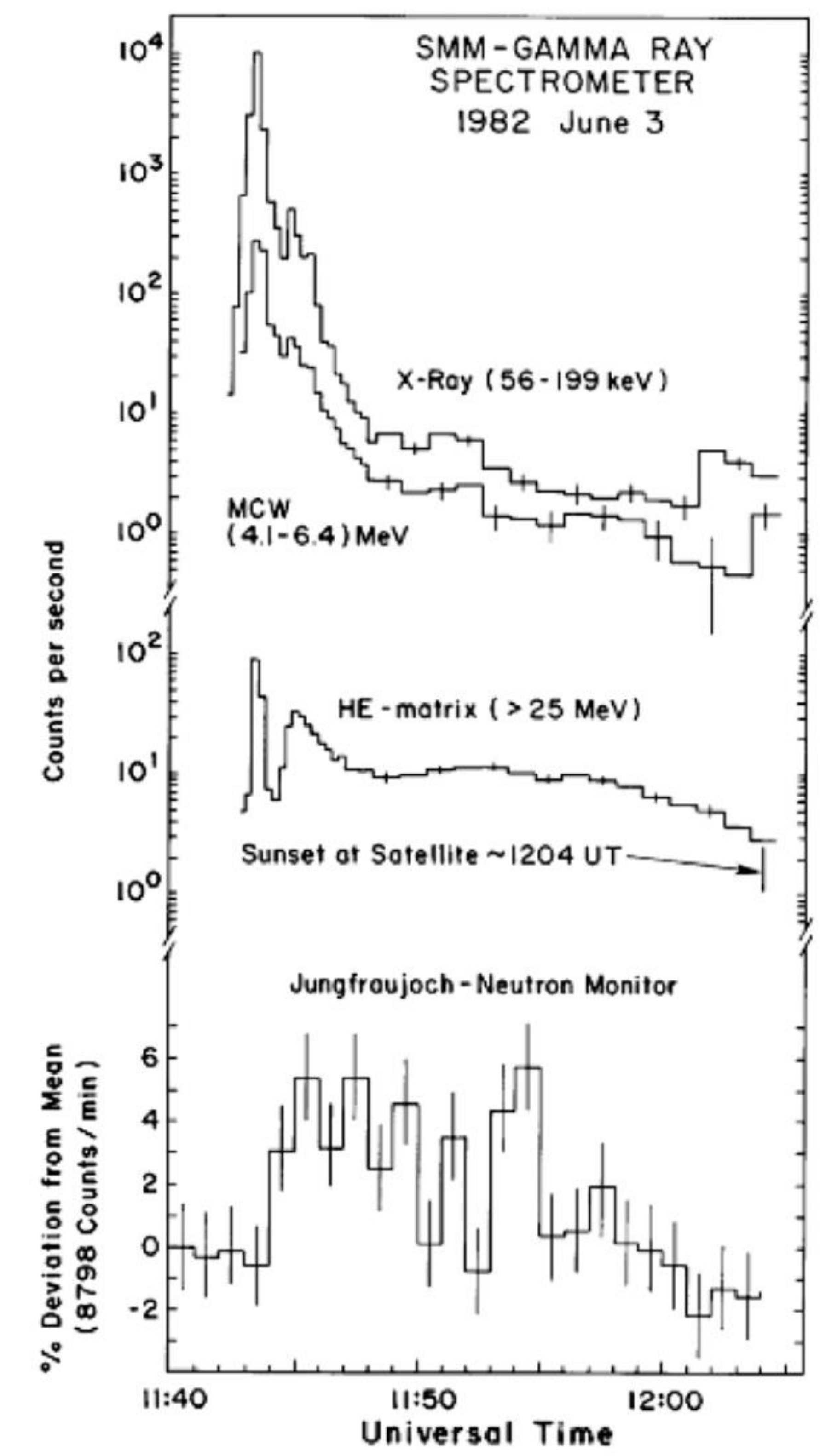

Figure 5. Neutral radiation from the solar neutron event on June 3, 1982. The top two plots show the photon and neutron measurements taken by the Solar Maximum Mission spacecraft and the bottom plot shows the neutron monitor response at Jungfraujoch. [7]

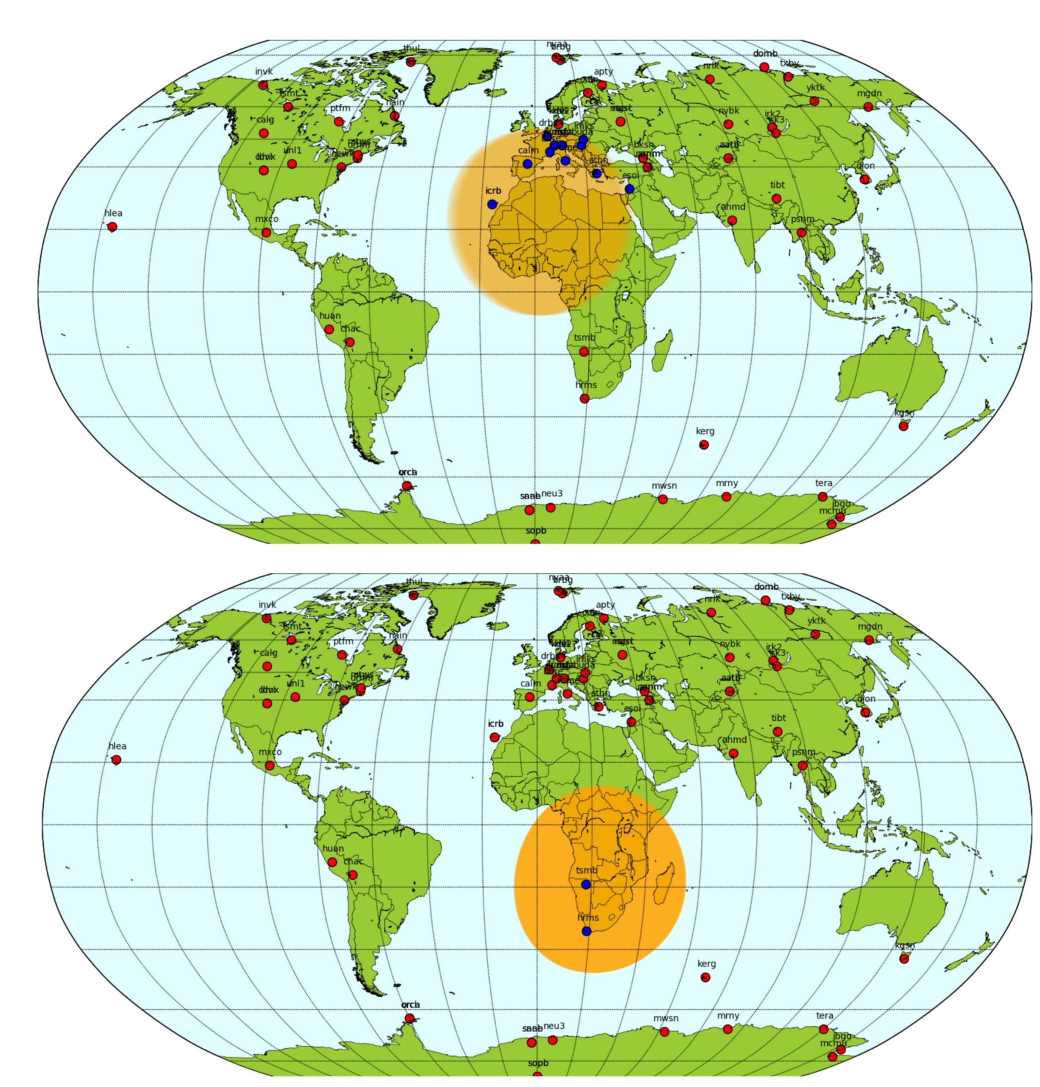

Figure 6. The best neutron monitor stations for observing a neutron signal during two strong events: June 06, 1982 (top) and Nov. 11, 2025 (bottom. The Nov. 11 event is actively being investigated for a ground level signal from solar neutrons.

References

[1] Simpson, John A. *Space Science Reviews* 93, no. 1 (July 1, 2000): 11–32.
[2] Hatton, C. J., and H. Carmichael. *Canadian Journal of Physics* 42, no. 12 (December 1964): 2443–72.
[3] Mishev, Alexander, and Ilya Usoskin. *Journal of Space Weather and Space Climate* 10 (2020): 17.
[4] Shibata, S. *Journal of Geophysical Research: Space Physics* 99, no. A4 (1994): 6651–65.
[5] Koga, K. et al. *Solar Physics* 292, no. 8 (August 14, 2017): 115.
[6] Usoskin, I. G. et al. *Annales Geophysicae* 15, no. 4 (April 30, 1997): 375–86.
[7] Chupp, E. L. et al. *The Astrophysical Journal* 318 (July 1, 1987): 913.
[8] Ryan, James M. *Space Science Reviews* 93, no. 3 (August 1, 2000): 581–610.
[9] Ajello, M. et al. *The Astrophysical Journal Supplement Series* 252 (February 1, 2021): 13.
[10] Rank, G. et al. *Astronomy and Astrophysics* 378 (November 1, 2001): 1046–66.
[11] Valdés-Galicia, J. F. et al. *Advances in Space Research*, Solar Extreme Events: Fundamental Science and Applied Aspects, 43, no. 4 (February 16, 2009): 565–72.
[12] Hua, Xin-Min et al. *The Astrophysical Journal Supplement Series* 140 (June 1, 2002): 563–79.
[13] Watanabe, K. et al. *The Astrophysical Journal* 636 (January 1, 2006): 1135–44.