

Remote Sensing of Plasma Conditions in the Heliosphere Using Neutron Monitor Measurements of Cosmic Rays. D. Ruffolo, Department of Physics, Faculty of Science, Mahidol University, Bangkok 10400, Thailand (david.ruf@mahidol.ac.th).

Introduction: Neutron monitors are ground-based detectors of primary cosmic ray ions via their showers in Earth's atmosphere. They are sensitive to particles that exceed an atmospheric cutoff energy (~ 1 GeV), for their showers to be detectable, and a local geomagnetic cutoff rigidity (varying from near zero in polar regions to ~ 17 GV in parts of Southeast Asia). Detecting atmospheric showers provides a much larger effective area than is available for space instruments, allowing high-precision cosmic ray measurements from a stable platform for nearly continuous, long-term data.

As charged particles, cosmic ray ions can be deflected by magnetic fields and scattered by magnetic fluctuations in the solar wind. The ions detected at a given time and location have collectively traveled or diffused across large volumes of the heliosphere. Plasma conditions in the heliosphere vary strongly with time: with the ~ 11 -year sunspot cycle, ~ 22 -year solar magnetic cycle, 27-day solar rotation, and solar storms, including coronal mass ejections (CMEs) and the shocks they drive before them. All of these are reflected in time variations of the cosmic ray flux, spectrum, and anisotropy. We briefly describe four specific examples of how neutron monitor observations provide unique remote sensing of plasma conditions and processes elsewhere in the heliosphere.

Fitting Solar Energetic Particle Profiles: A neutron monitor always detects Galactic cosmic rays (GCRs) above its cutoff rigidity (energy). In addition, during each sunspot cycle there are some solar storm events that accelerate ions to relativistic energies at a flux detected above the GCR background for hours or days, which are termed ground level enhancements (GLEs). By precision modeling of the interplanetary transport of relativistic solar particles, we have inferred special magnetic configurations in interplanetary space, such as magnetic bottlenecks [1] and magnetic loops [2]. We have also determined the scattering mean free path of relativistic ions, which relates to magnetic turbulence between the Sun and the Earth.

Solar Modulation of Galactic Cosmic Rays: GCRs undergo significant flux variations over the sunspot cycle, a phenomenon known as solar modulation. A polar neutron monitor may observe a flux variation of $\sim 15\%$. Data have been collected from numerous neutron monitors for several solar cycles [3]. In parallel, there have been great advances in 1) models of solar wind turbulence and its transport through the heliosphere, as informed by spacecraft

measurements along certain trajectories (mostly near the Ecliptic plane), and 2) theories of cosmic ray transport [4]. While many challenges remain, neutron monitors provide important constraints on modeling of solar wind turbulence and transport theories.

Anisotropy during Forbush Decreases in Galactic Cosmic Rays: As a shock and/or CME pass Earth, neutron monitors can register a so-called Forbush decrease in the GCR flux. While Earth is inside the magnetic flux rope of a CME, plasma turbulence can be weak and relativistic particles may have a mean free path of ~ 1 AU [2,5]. Therefore, the GCR anisotropy inside a flux rope can provide direct information about distant plasma processes. In particular, there was a prediction that cosmic rays drift into a CME flux rope along one leg and out the other, which should generate a unidirectional anisotropy [6]. Such anisotropy has been confirmed by neutron monitor data [7].

Two-Week Modulation Events: In contrast with a Forbush decrease in the GCR flux at the time of a shock and/or CME, with a rapid onset and slower recovery over a few days, recent work has noted two time periods in 2012 with a slow decrease in the GCR flux and similarly slow recovery, over a total of two weeks, along with a remarkably strong anisotropy [8]. This can be explained as the non-local effect of a shock or sequence of shocks that already passed the Earth as they block GCR access. The anisotropy indicates diffusive inflow of cosmic rays perpendicular to the large-scale magnetic field, with a mean free path similar to that estimated from an existing theory of perpendicular diffusion [9].

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References: [1] Bieber, J. W., et al. (2002) *ApJ*, 567, 622 [2] Ruffolo, D., et al. (2006) *ApJ*, 637, 1186. [3] Moraal, H. (1976) *SSRv*, 19, 845. [4] Engelbrecht, N. E., et al., in preparation [5] Bieber, J. W., et al. (2005) *GeoRL*, 32, L03S02. [6] Krittinatham, K. and Ruffolo, D. (2009) *ApJ*, 704, 831. [7] Tortermun, U., et al. (2018) *ApJL*, 852, L26. [8] Buattaisong, N., et al. (2021) *ICRC*, 1262. [9] Ruffolo, D., et al. (2012) *ApJL*, 747, L34.