

Estimates of Solar Modulation Potential to Support Lunar Exploration and Volatiles Prospecting with the Neutron Spectrometer System

Abstract
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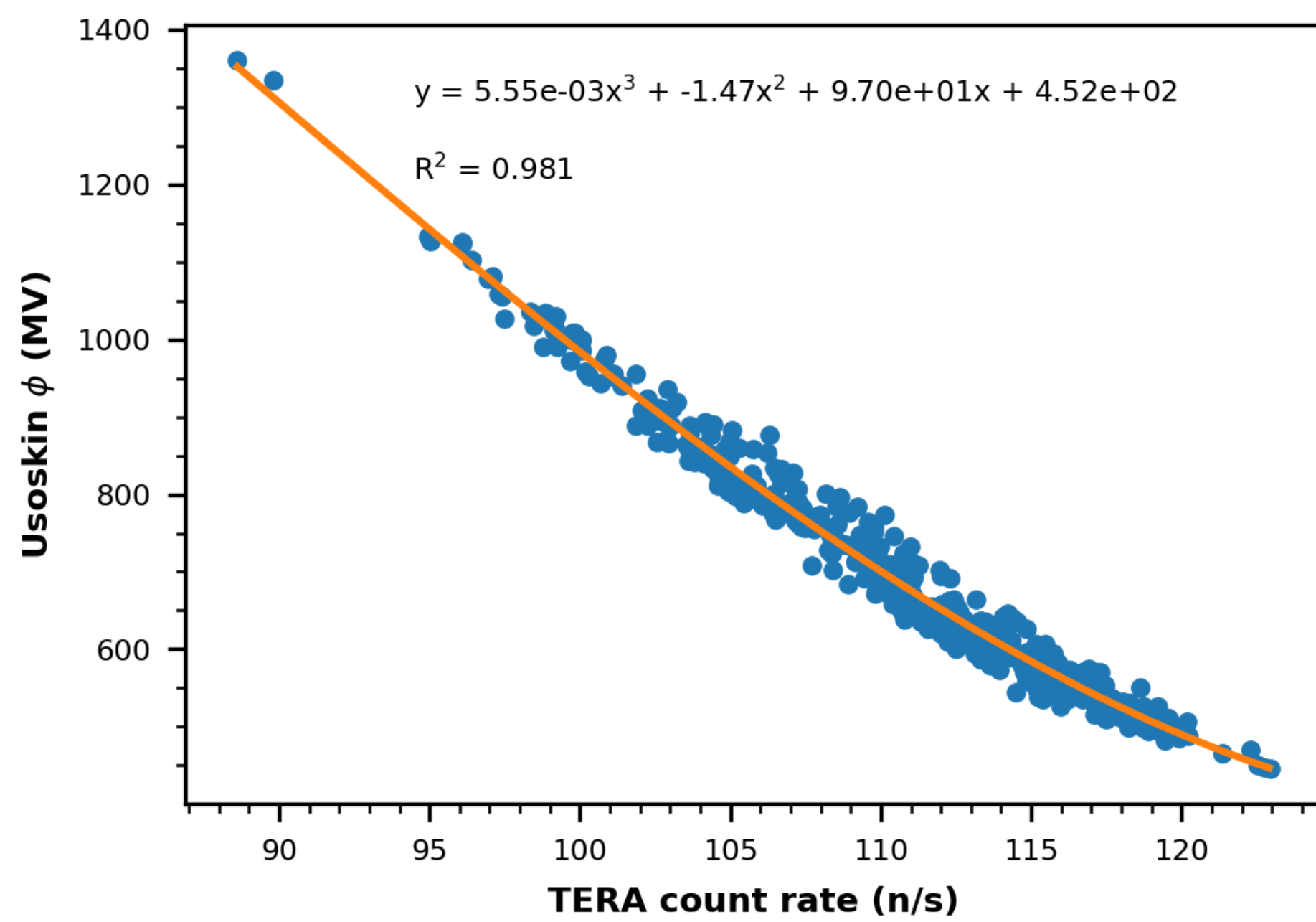
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Three methods for determining Solar Modulation Potential (ϕ):

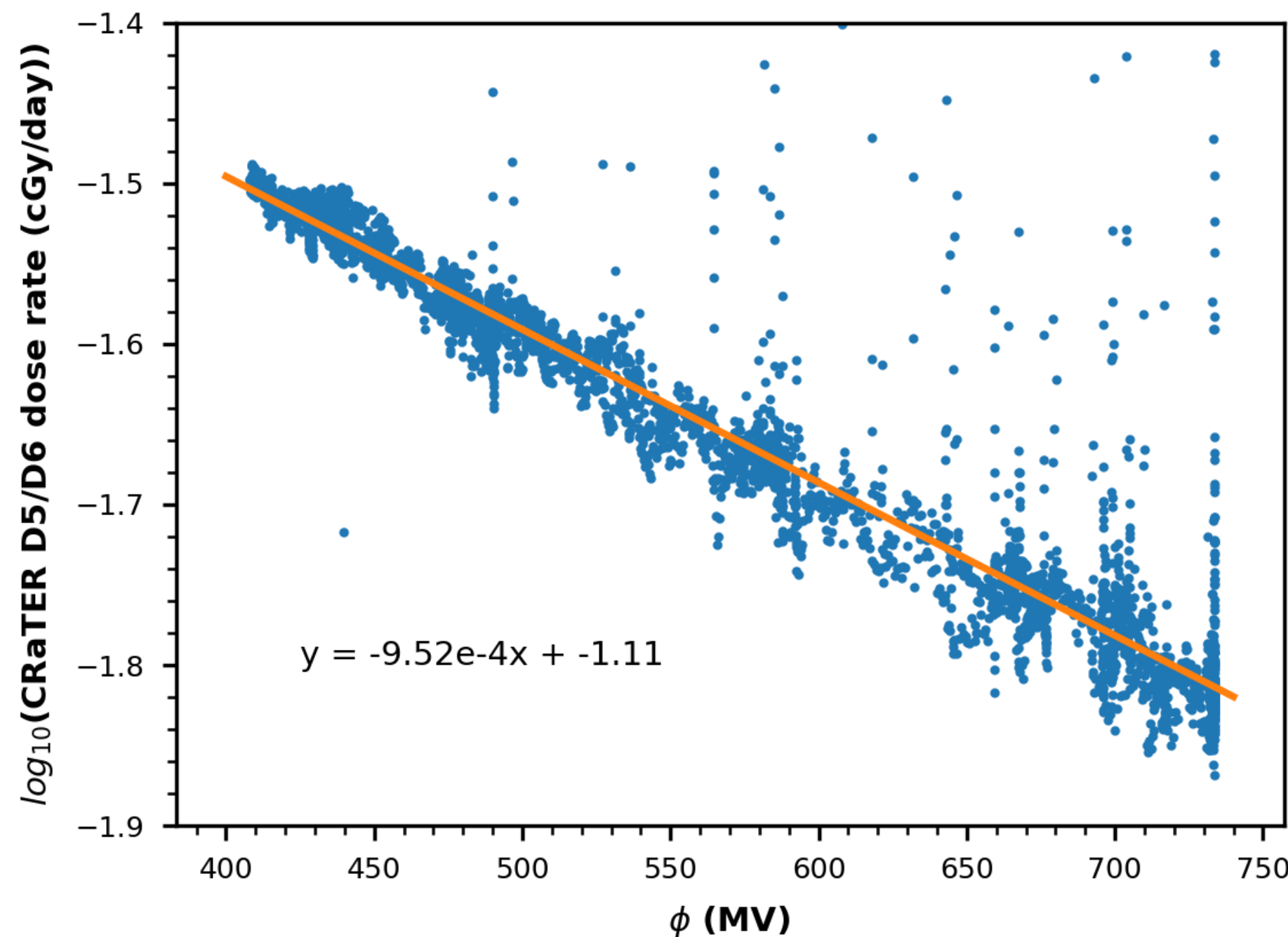
Terrestrial Neutron Monitors

Neutrons produced by the interaction of GCRs with Earth's atmosphere are measured at stations around the planet and reported by the Neutron Monitoring Database (NMDB). We fit 3rd order polynomials to historical count rates plotted against ϕ from Usoskin et al. (2017) (right) [13]. Neutron count rate data are provided in near real-time by the NMDB.



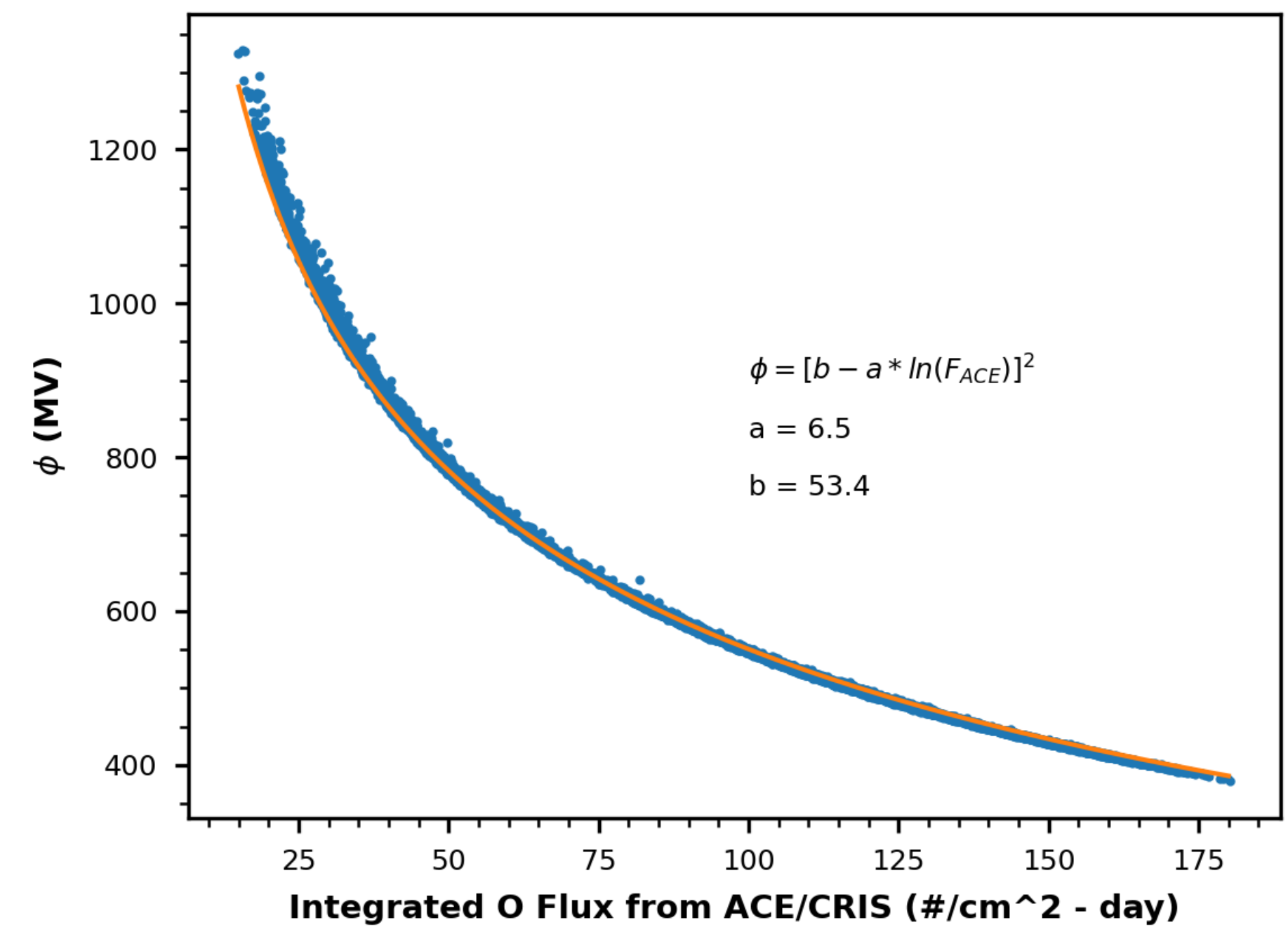
Lunar Reconnaissance Orbiter (LRO) Cosmic Ray Telescope for the Effects of Radiation (CRArTER)

Lineal energy transfer (LET) spectra from the CRArTER instrument can directly provide estimates of the flux of GCRs. Secondly, absorbed dose rates from CRArTER were used by de Wet et al. 2020 to estimate ϕ (right) [14]. While LRO is in the most similar environment to NSS, CRArTER data is available only after LRO downlink (~1-5 days).



Advanced Composition Explorer (ACE) Cosmic Ray Isotope Spectrometer (CRIS)

Fluxes of cosmic rays with $Z > 5$ are measured by the ACE CRIS Instrument and reported by the ACE Science Center. Slaba and Whitman (2020) provided exponential relationships between the integrated fluxes from CRIS and solar modulation (right) [15]. While CRIS data are the most direct measure of GCRs presented here, they are only available after each Bartels' rotation (27 days).



Summary: We show how terrestrial neutron count rates, dose rates from LRO CRArTER, and measurements of cosmic rays from ACE/CRIS can be used to estimate solar modulation potential and thus the flux of galactic cosmic rays. More accurate estimates of buried volatile content from neutron count rates on the lunar surface can be provided when the cosmic ray flux is constrained.

Background – NSS: Over the next several years, at least three flight units of the Neutron Spectrometer System (NSS) will be sent to the lunar surface (Fig. 1) [1, 2, 3]. This instrument measures thermal ($E < 0.4$ eV) and epithermal ($0.4 < E < \sim 100$ keV) neutrons at the lunar surface. Variation in the count rates of these two populations will be used to infer the abundance of volatiles, particularly H [e.g., 4, 5, 6]. The measured count rates vary as a function of subsurface composition and changing galactic cosmic ray (GCR) flux (Fig. 2).

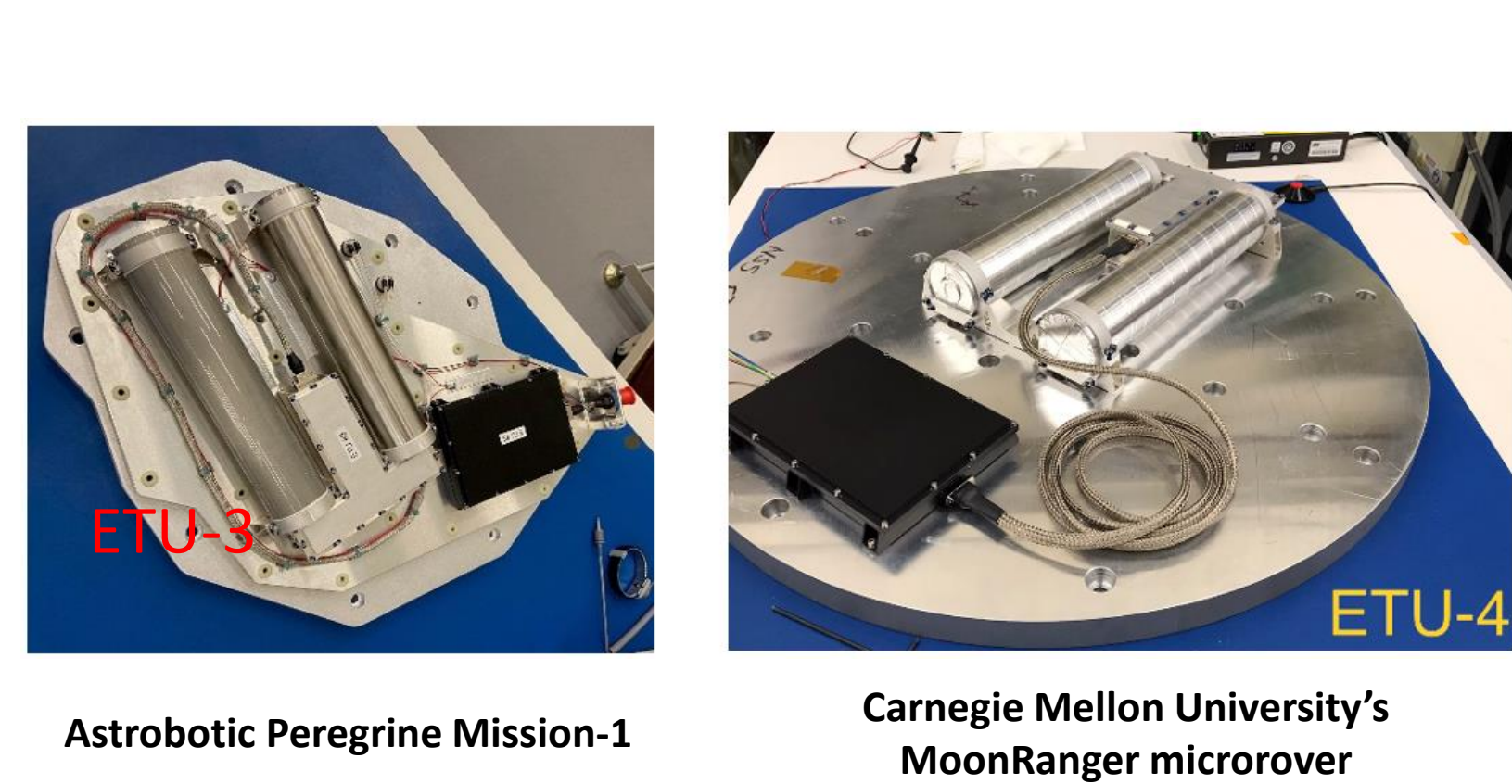


Figure 1. The Neutron Spectrometer System will measure neutrons exiting the lunar surface to make estimates of subsurface hydrogen content. The VIPER NSS unit is not shown here.

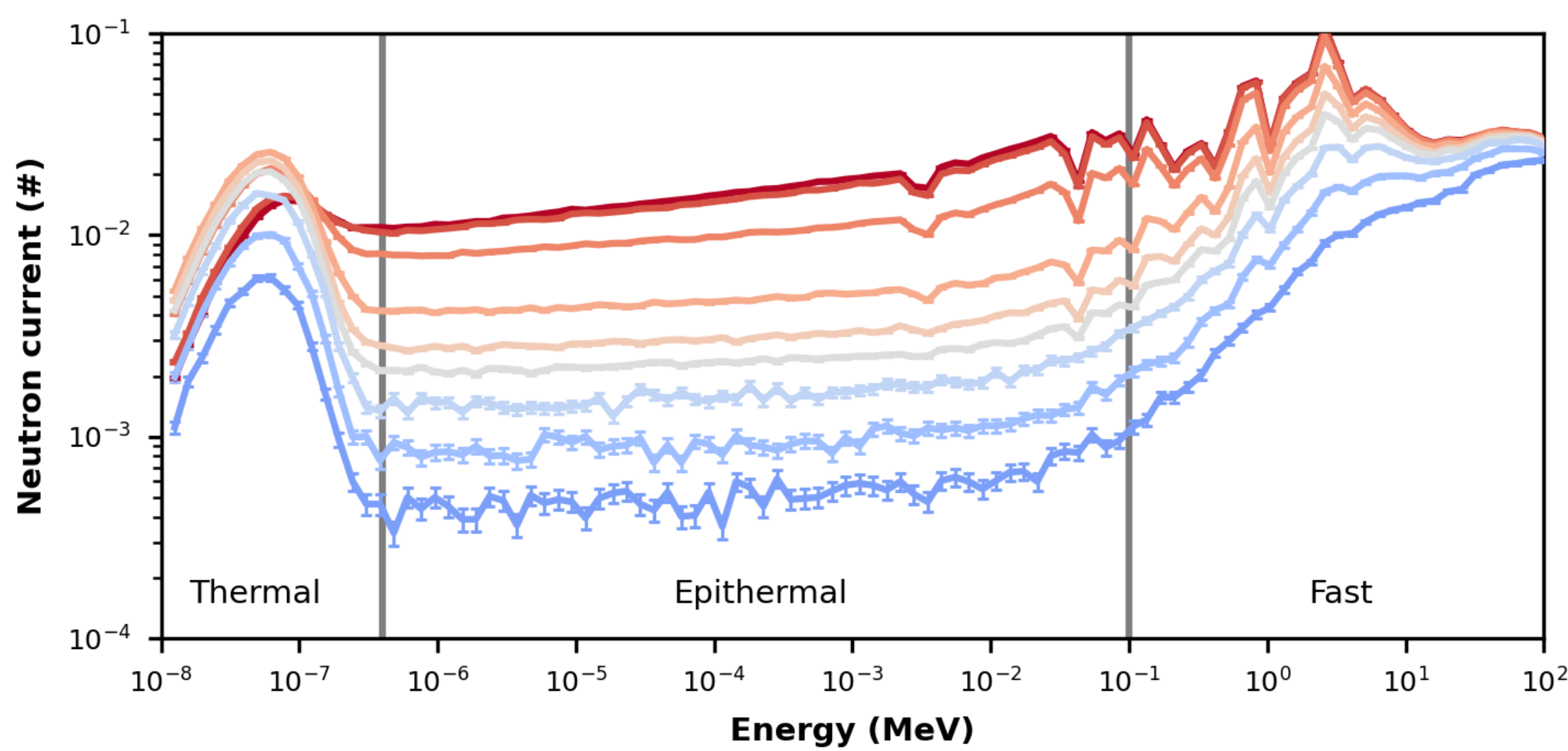


Figure 2. Simulated neutron leakage current from the lunar surface. Simulations use a FAN regolith with (from top to bottom) 0, 0.09, 0.9, 4.5, 9, 13.5, 18, 45, and 90 wt.% H₂O.

Background - GCRs: Galactic cosmic rays are extrasolar energetic particles composed of ~98% ionized nuclei and 2% electrons [7]. In the energy range where GCRs have the highest intensity (10^8 - 10^{10} eV/nucleon) and during periods of low solar activity, the nuclear component is ~87% protons, ~12% alpha particles, and ~1% all other nuclei [7].

GCRs enter the solar system isotropically and interact with nuclei in planetary surfaces, generating secondary radiation, including neutrons [8]. These neutrons interact further with subsurface nuclei and may exit the surface to be measured by instruments like NSS [8].

While the GCR flux is relatively spatially constant at 1 AU, the flux of GCRs at energies $< \sim 1$ GeV/nucleon varies with the ~11-year solar cycle (Fig. 3) [9, 10]. Models of GCR spectra can be parametrized with a single time-dependent factor called the **solar modulation potential**, or ϕ [e.g., 11]. These models (e.g, Eq. 1) can be used to estimate the flux of GCRs, and thus properly computing ϕ is critical for interpreting NSS data.

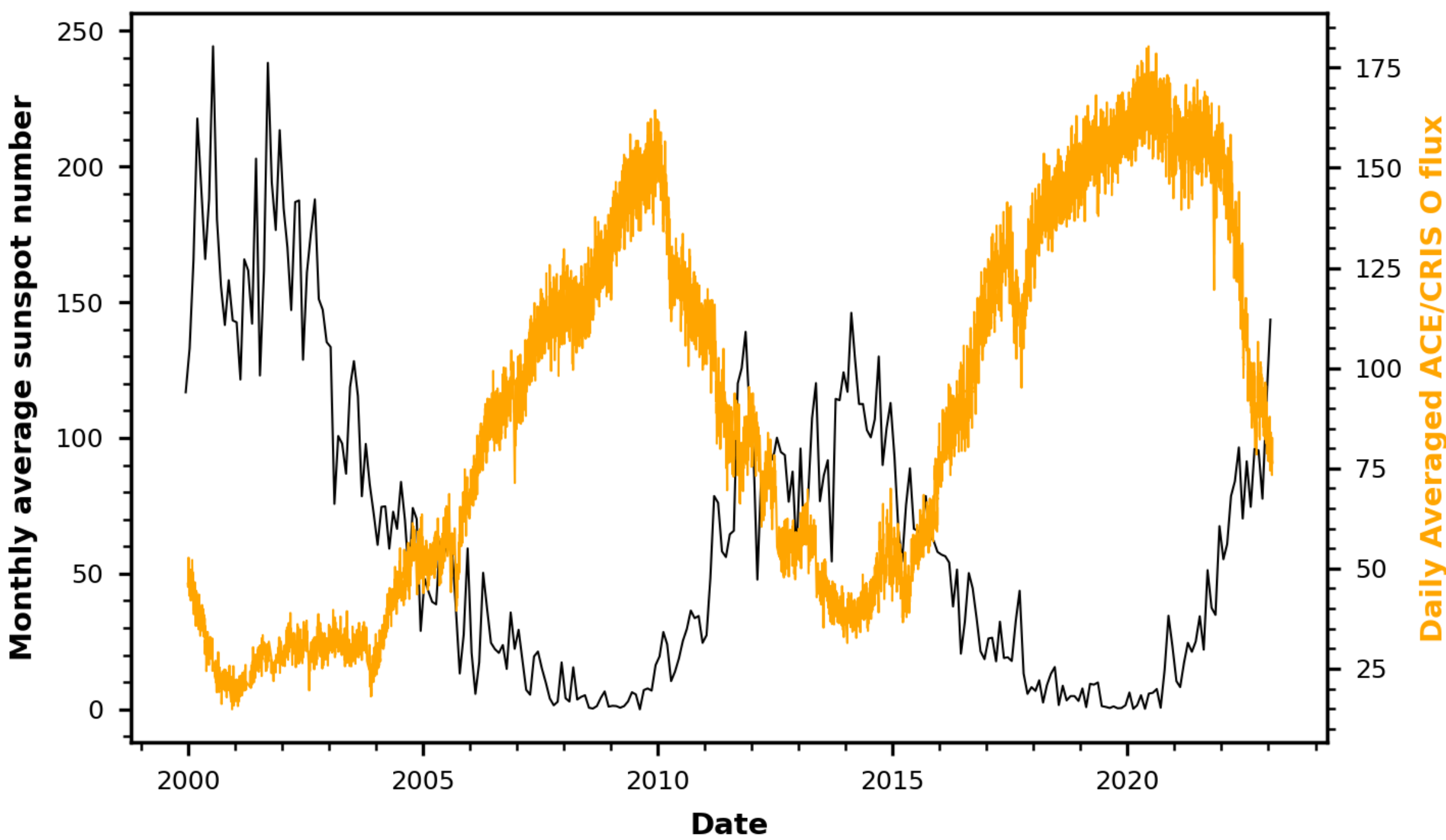


Figure 3. The flux of GCRs (measured through the integrated O flux measured by the ACE/CRIS instrument) is anticorrelated with solar activity (expressed through sunspot number). The sunspot numbers come from WDC-SILSO, Royal Observatory of Belgium, Brussels. We thank the ACE CRIS instrument team and the ACE Science Center for providing the ACE data.

Equation 1. Omnidirectional GCR Formulation from [11], corrected by Masarik and Reedy [12].

$$G(T, \phi) = A \frac{T (T + 2E_0) (T + m + \phi \frac{Z}{a})^{-\gamma}}{(T + \phi \frac{Z}{a})(T + 2E_0 + \phi \frac{Z}{a})}$$

$G(T, \phi)$ - spectral flux of a GCR particle ($\#/\text{cm}^2\text{-s-MeV}$)
 T - particle energy (MeV)
 ϕ - solar modulation potential (MV)
 A - fit coefficient (see table below for values)
 E_0 - particle rest energy (MeV)
 z - particle atomic number
 a - particle atomic mass number
 m - $p * \exp(-b*T)$ (MeV, see table below for values)

Particle	A	p (MeV)	b (MeV ⁻¹)	γ
Protons	1.24e6	780	2.5e-4	2.65
Alphas	2.26e5	660	1.4e-4	2.77

Why does it matter? Models used to interpret neutron count rates (e.g., Fig. 2) must be scaled by “source particles” (i.e., GCR flux) to get to units comparable with measurements from NSS. **Variation in the GCR proton flux by ~0.5 proton/cm²-s (e.g., Fig 4D) translate to uncertainty in the inferred H content of XX wt. % H.**



Figure 4. (A) Values of ϕ from the three methods for the last solar cycle; (B) the integrated omnidirectional GCR proton flux for the same time period, computed using Eq. 1; (C,D) same as A and B but for a 100-day period (gray vertical band in A and B), similar to the planned VIPER mission duration. The methods presented here support difference cadences of tactical decisions.

Further questions:

- How does the varying GCR alpha/proton ratio as a function of ϕ affect neutron production?
- How do higher Z GCRs affect neutron production? What are the coefficients for Eq. 1 for higher Z GCRs?
- What is the best method for consolidating the multiple estimates of ϕ for post-mission data analysis?
- Can sunspots (published daily) be used as another method for estimating ϕ and thus GCR flux?

References: [1] Colaprete, A. et al. (2019) AGU Fall Meeting, P34B-03. [2] Voosen, P. (2018) Science, 362(6417), 875-876. [3] Schweitzer, L. et al. (2020) AGU Fall Meeting, P023-0012. [4] Feldman, W. et al. (1998) Science, 281, 1496-1500. [5] Elphic, R. et al. (1998) Science, 281, 1493-1496. [6] Lawrence, D. et al. (2006) JGR, 111(E08001), 1-19. [7] Simpson, J. (1983) Ann. Rev. Nucl. Part. Sci., 33, 323-381. [8] Prettyman, T. (2014) Encyclopedia of the Solar System, 1161-1184. [9] Gleeson, L. and Axford, W. (1968) Ap. J., 154, 1011-1026. [10] Wiedenbeck, M. (2013) Space Sci. Rev., 176, 35-46. [11] Castagnoli, G. and Lal, D. (1980) Radiocarbon, 22(2), 133-158. [12] Masarik, J. and Reedy, R. (1996) JGR: Planets, 101(E8), 18891-18912. [13] Usoskin, I. et al. (2017) JGR: Space Physics, 122, 3875-3887. [14] de Wet, W. et al. (2020) Life Sciences in Space, 26, 149-162. [15] Slaba, T. and Whitman, K. (2020) Space Weather, 18, e2020SW002456.