LRO CRaTER and the Radiation Environment Measured near the Moon: Implications of Lunar Destinations for Human Explorers

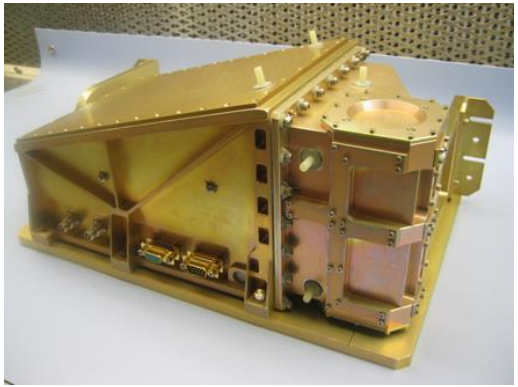
Harlan E. Spence and Sonya S. Smith

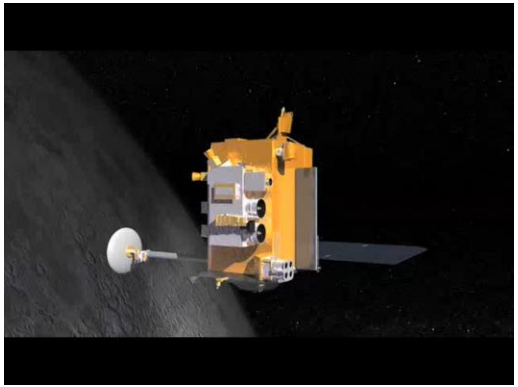
On Behalf of the

CRaTER Project Team

Space Science Center

University of New Hampshire





NAS LDHE Panel, 12 August 2025, Irvine, CA

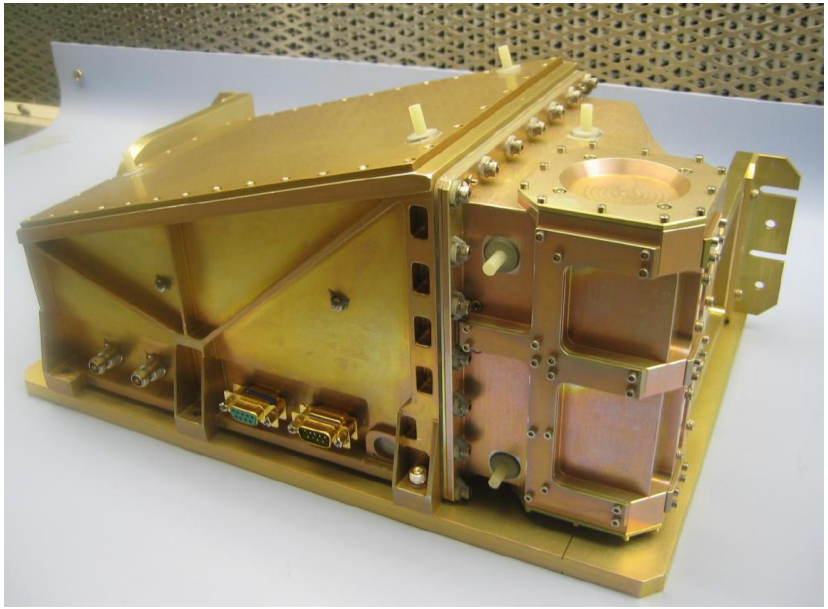
CRaTER ESMD Measurement Goals

Goals of this presentation:

- Review measurements from LRO's CRaTER instrument with focus on those studies that are most relevant to questions posed by the NAS LDHE panel:
    - What are the properties of radiation shielding by regolith?
    - Does radiation shielding differ according to location?
    - Are charging effects different in different regions?
    - What investigations must be conducted *in situ* to inform these applied science/engineering questions?
- Presentation contains material with greater depth than I can cover in 15 minutes, but is provided for completeness and with your study in mind

Cosmic Ray Telescope for the Effects of Radiation (CRaTER) Investigation

- Launched on NASA's Lunar Reconnaissance Orbiter (LRO) in June 2009
- Nadir/Zenith viewing along "telescope" axis
- Designed to estimate Linear Energy Transfer of galactic cosmic rays and solar protons near the Moon



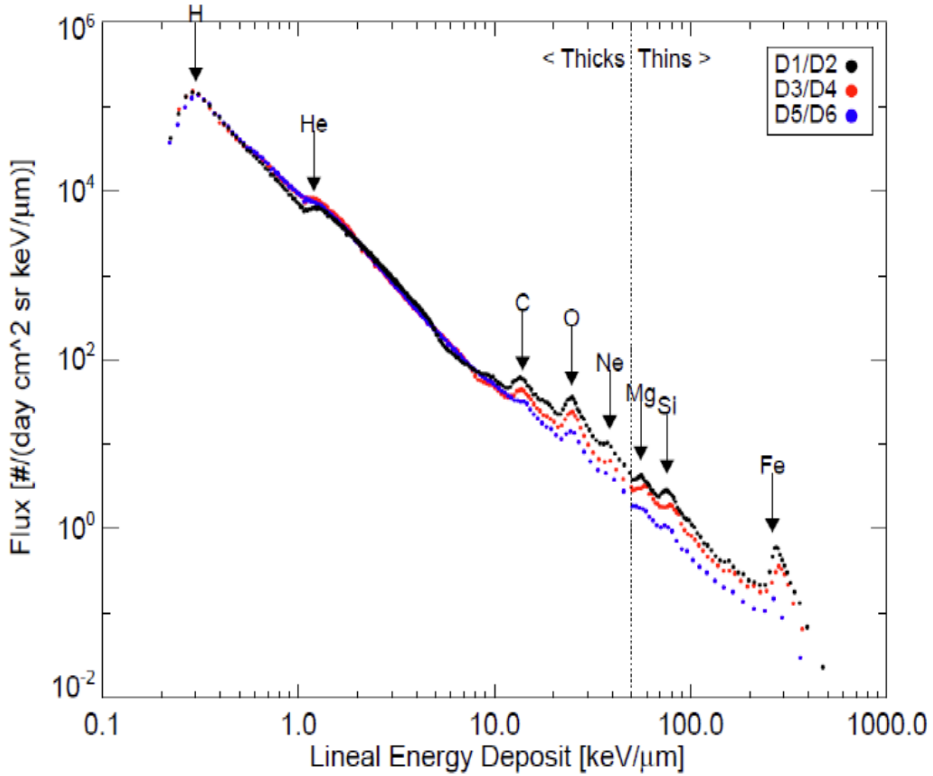
(Spence et al., Space Sci. Rev., 2010)

CRaTER ESMD Measurement Goals

To characterize the global lunar radiation environment and its biological impacts

- Six-element, solid-state detector and tissue-equivalent plastic (TEP) telescope
- Sensitive to cosmic ray particles with energies greater than ~10 MeV, primarily protons (but also heavy ions, electrons, high energy photons, neutrons, and other subatomic stuff)
  - *Galactic cosmic rays – GCRs*
  - *Solar energetic particles– SEPs*
- Measure spectrum of Linear Energy Transfer (LET = energy per unit path length deposited by cosmic rays as they pass through or stop in matter) behind different amounts of TEP
- Accurate LET spectrum was missing link needed to constrain radiation transport models and radiation biology

LET Spectra & Shielding: Galactic Cosmic Rays



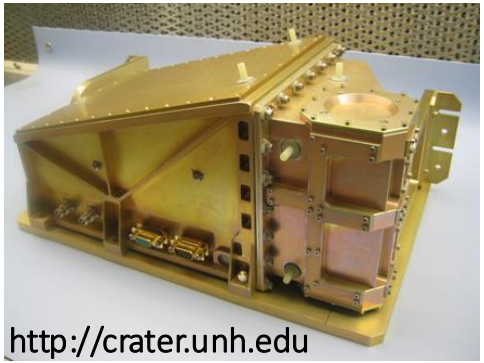
After Case et al., 2013; Zeitlin et al., 2013; and Porter et al., 2013

- CRaTER is providing high-resolution estimates of LET from GCR over the course of the mission
- Thin-thick pairs permit exploration of the LET spectrum from the low end, dominated by protons to the high end dominated by heavy ions
- Evolution of LET through the various sections of TEP are allowing us to explore and test theories of space radiation shielding

LRO and the “Wargo Axiom”

“Science enables Exploration; Exploration enables Science”

Design driven by human exploration, but nimble enough for innovative science

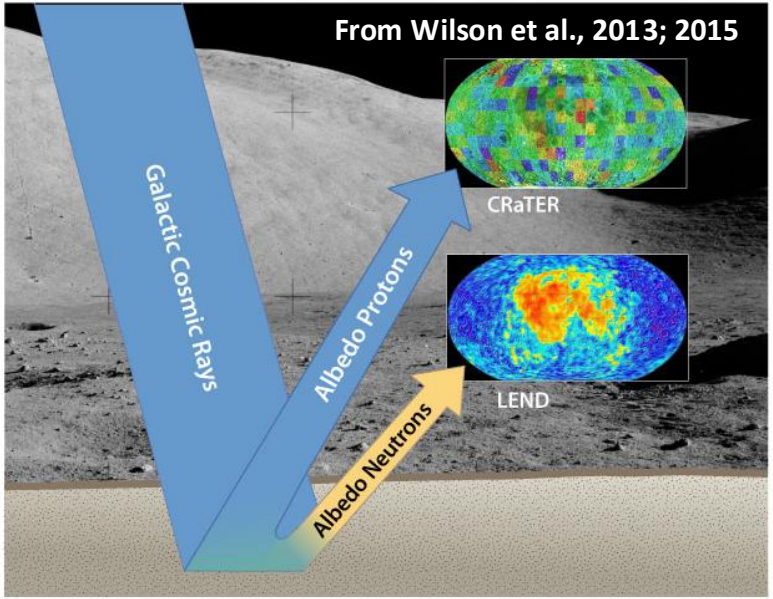


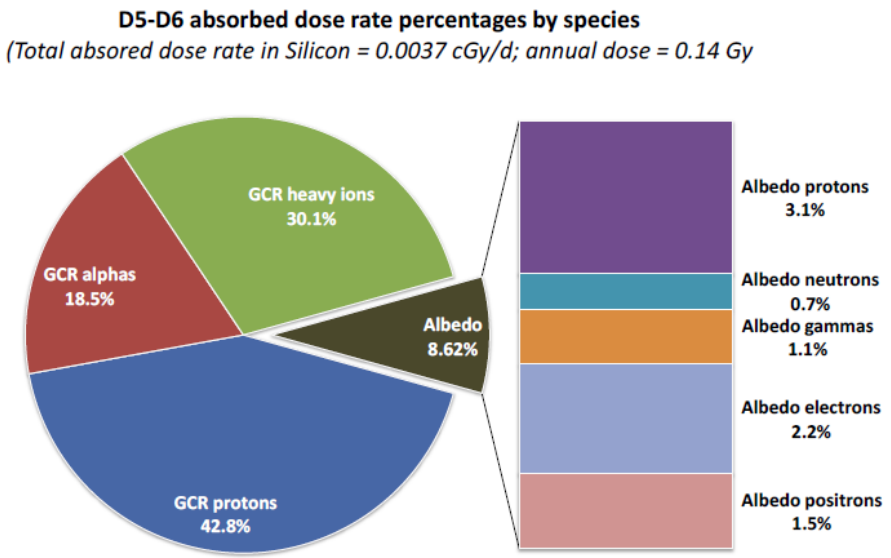
“Luna Ut Nos Animalia Tueri Experiri Possimus (Luna TEP)”
(“In order that we might be able to protect and make trial of living things on the Moon”)

NASA LRO CRATER
UNH - BU - MIT - AEROSPACE - SAO - UTK

Lunar Science Enabled by Exploration

- GCR primaries give up energy and produce secondaries
- Escaping secondary interactions with regolith provide tell-tale signs of material they traversed
  - Ex: Neutron/gamma lunar imaging used to probe regolith for subsurface regions of hydration



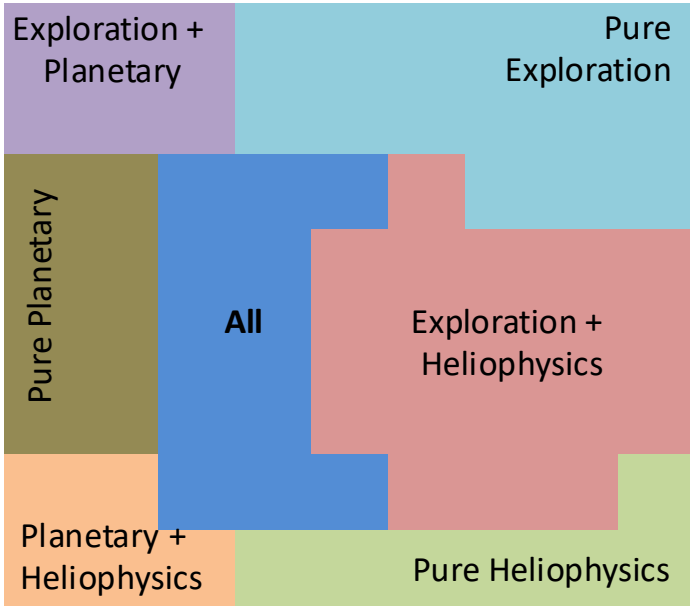


From Spence et al., 2013

- **GCR primaries (and secondaries!) provide not only an ionizing radiation source, but also a means for scientific exploration of the lunar surface**

Several Representative Vignettes Demonstrating Interplay between Lunar Exploration and Lunar Science

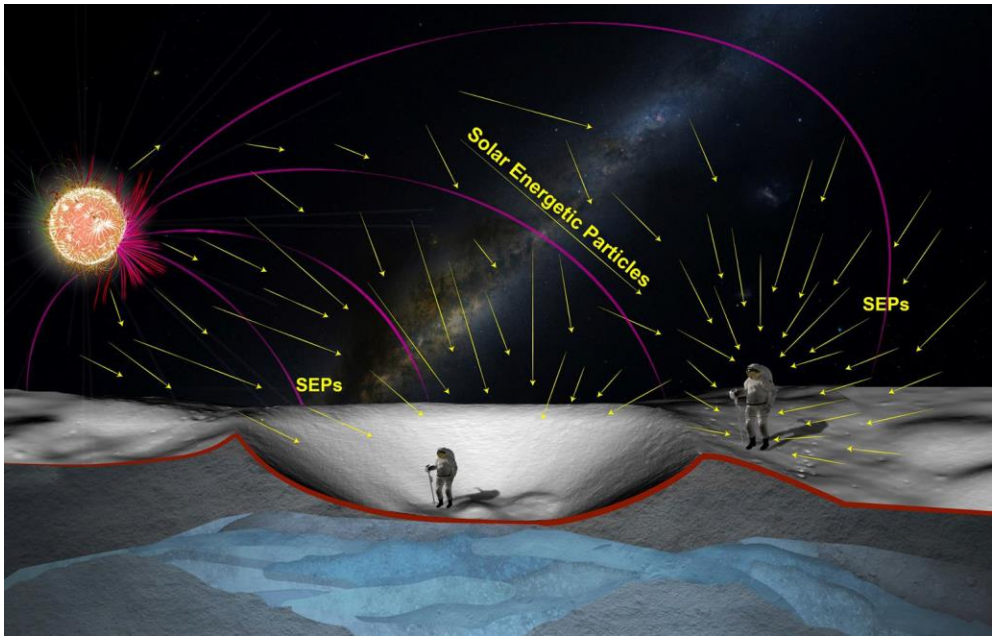
Relative distribution of all CRaTER publications during LRO mission according to topical foci of paper



Vignette #1.

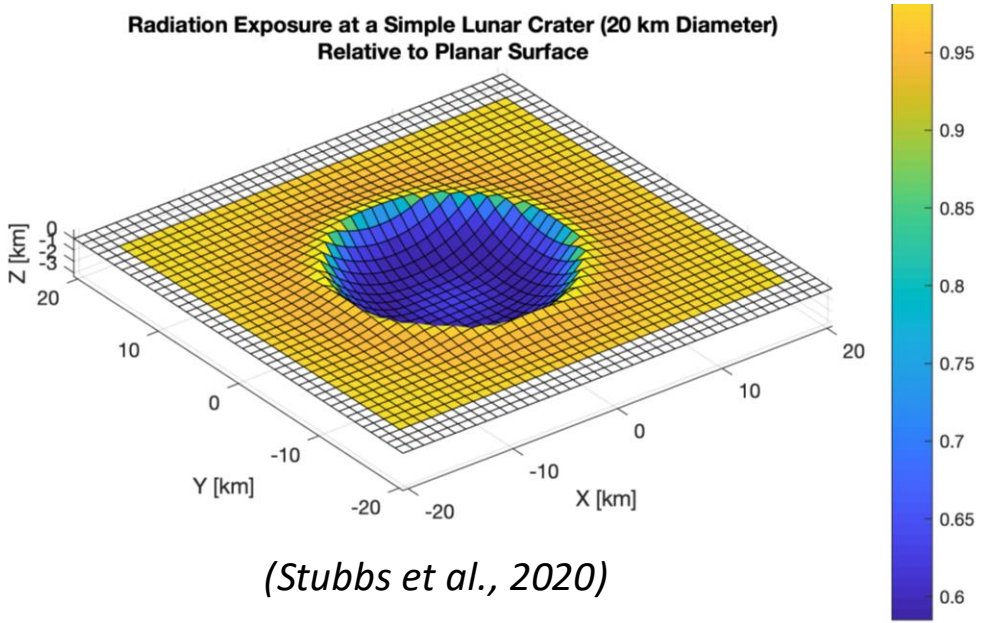
Lunar Surface Radiation Mapping Including Measured Topography: Surface Features Produce Localized Radiation Shielding

- Work lead by Tim Stubbs and Phillip Phipps (NASA/GSFC)



On Beyond the Spherical Cow

- Estimate radiation exposure relative to a planar surface where topography provides natural shielding from GCR exposure
- Values <1.0 indicates that shielding is provided by terrain relative to a locally planar surface

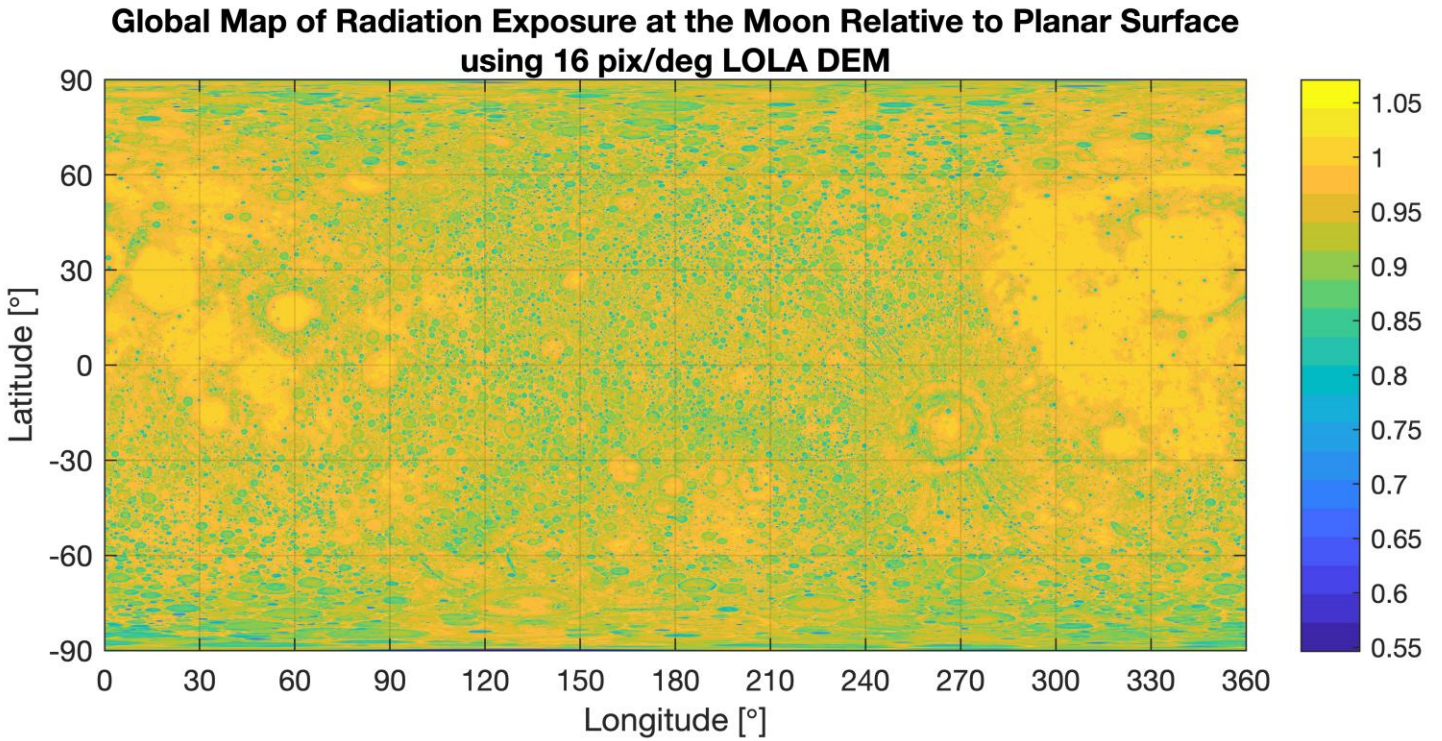


(Stubbs et al., 2020)

- By way of example, we show a simple lunar crater w/ 20 km diameter and 3 km depth
- Crater (not CRaTER) walls provide shielding from portion of sky, thus decreasing net exposure by ~40% in this case

Act Locally, Think Globally

- Global map of relative radiation exposure at 16 pixels per degree (<2 km per pixel) using LOLA DEMs
- Computationally intense!

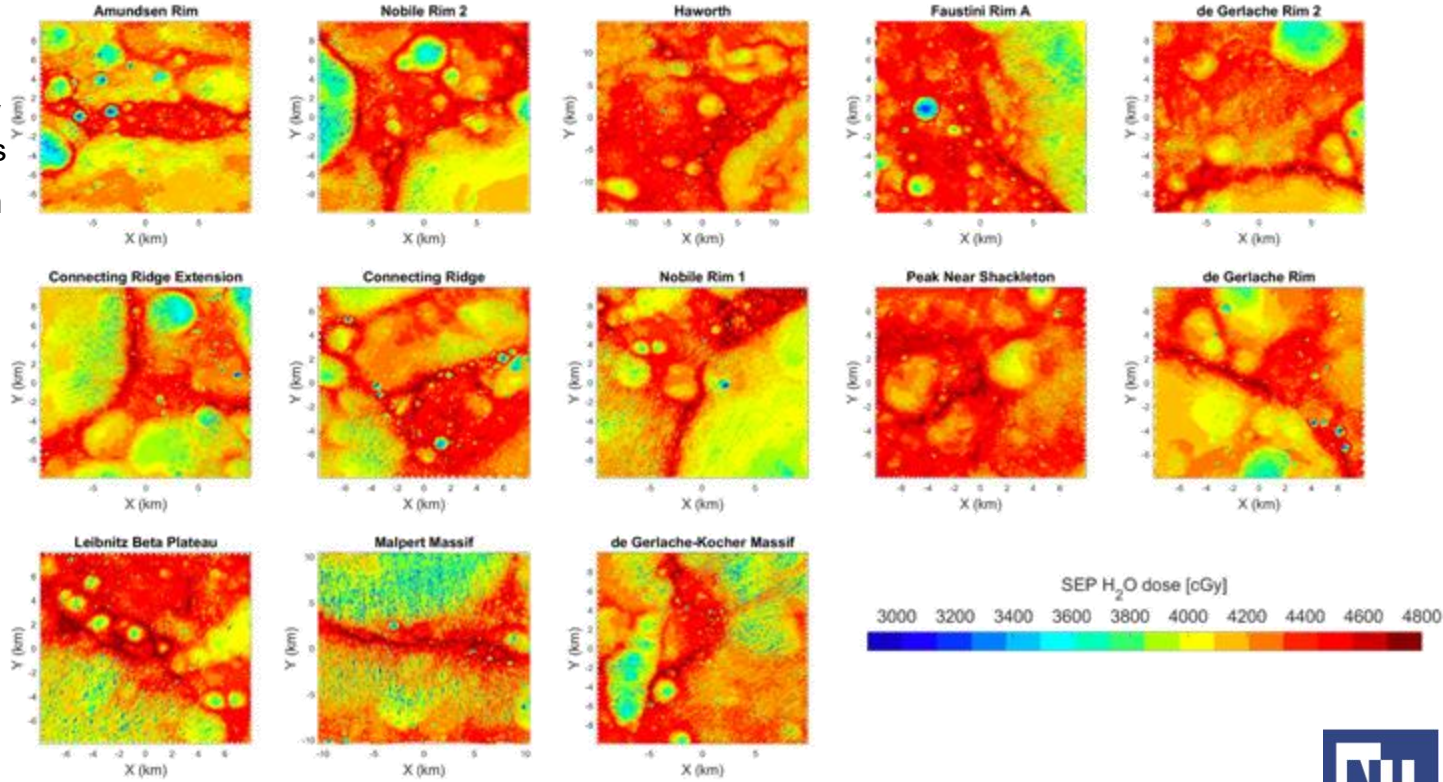


(Phipps et al., 2022)

Artemis III Landing Site Assessments

- Radiation dose from SEP events can be extremely hazardous
- Radiation Exposure differs by <10% between the 13 regions
- Most regions offer better than average shielding (when compared to South Pole)
- Predictive location-specific models critical to developing effective mitigation strategies
- Locations identified for exploration (e.g., the rim of Shackleton crater) are associated with an increased risk of radiation exposure relative to other locations on the lunar surface

Maps of Predicted Radiation Dose to an Astronaut for October 1989 SEP (Worst Case Scenario)



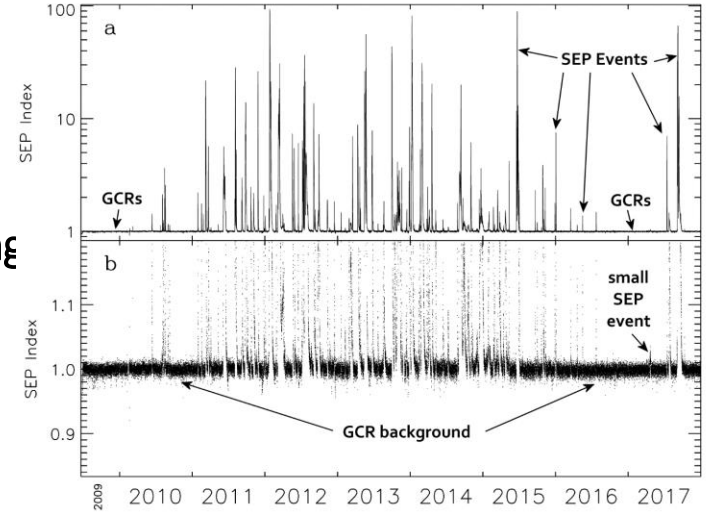
Vignette #2.

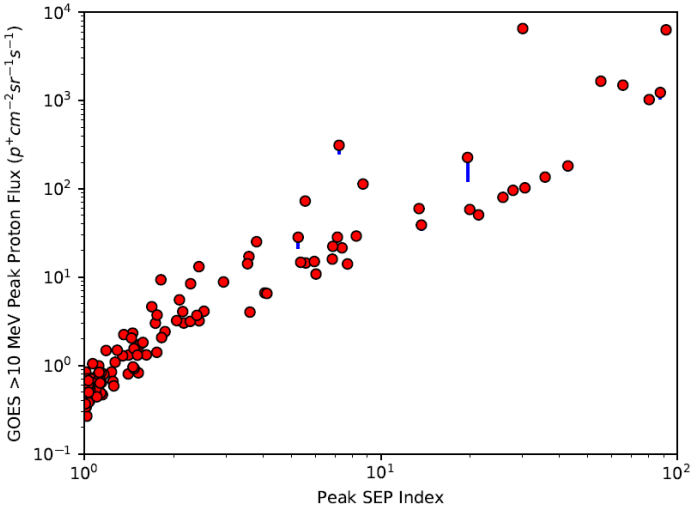
Precise Detections of Solar Particle Events and a New View of Secondary Radiation Emerging from Regolith: Secondary Radiation Varies With Regolith Composition

- Jody Wilson (UNH) lead

“If thine eye offend thee, then pluck it out…”

- GCR (low flux, incessant, high energy) and Solar Protons (intense flux, episodic, lower energy) yield different lunar radiation environments
- Serendipitous SEPI invented to “pluck out” offending solar proton events from background



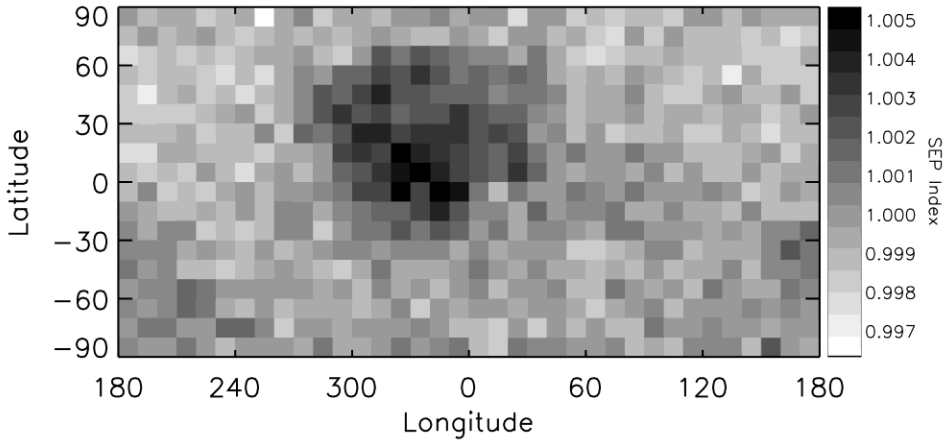


(Wilson et al., 2019)

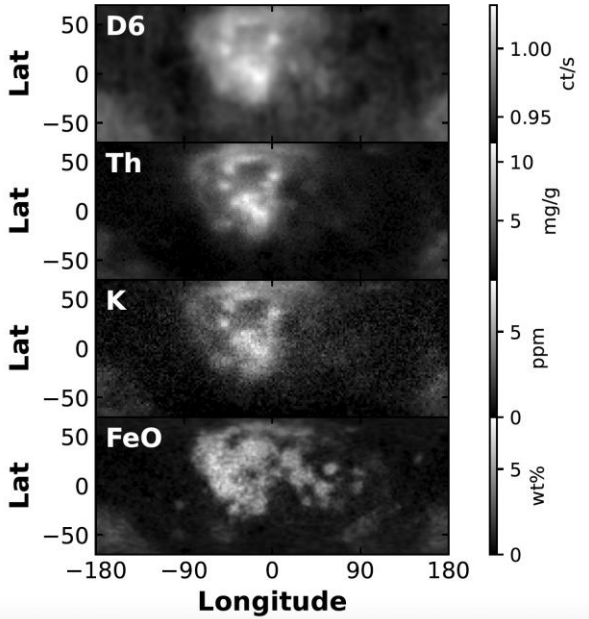
- SEPI correlated with traditional solar p+ measures (GOES PFU)
- SEPI is an as-yet fully quantified combination of lunar albedo protons, neutrons, and gamma rays (work in progress)

From Trash to Treasure – SEPI Rehabilitated!

- Take SEPI (constructed in time domain from CRaTER's simple secondary science data) and map it spatially
- Unlike all earlier CRaTER albedo maps, SEPI map looks like Moon with ease!
- Refined map ("D6" in right figure) closely resembles LP gamma-ray maps Th, K, and FeO



(Wilson et al., 2020)



(Jordan et al., work in progress, 2025)

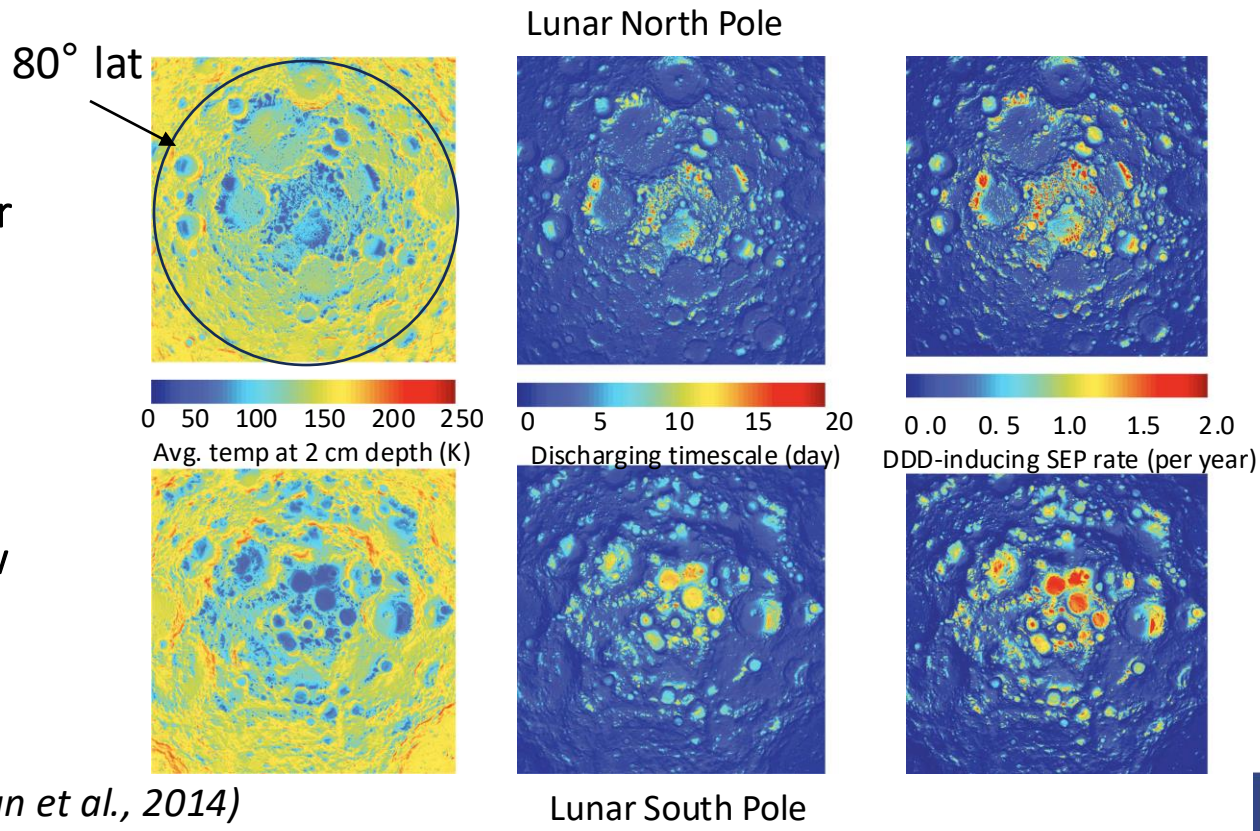
Vignette #3.

Spatial Distribution of Deep Dielectric Discharging (DDD) of Regolith: Avoid the Poles!

- Work led by Andrew Jordan (UNH)

DDD Effects Maximize in PSRs near Poles

- Solar particles can differentially charge regolith, setting up electric fields in the near surface regolith
- If charging rate exceeds dielectric properties, discharge can occur
- Temperature key to discharge likelihood; low temps in PSRs are most prone to DDD



(Jordan et al., 2014)

Summary and Conclusions

- Measurements from LRO's orbit **quantify** the global radiation environment (primary and secondary) **near** the Moon and they **provide insights** about the radiation environment at the **surface** of the Moon → Need measurements at the surface to validate extension of LRO's orbital measurements to surface
- Natural shielding of primary sources of ionizing radiation occurs owing to lunar topography → Optimize landing site position to maximize natural shielding
- Secondary radiation varies with location owing to compositional variability of lunar regolith → Choose landing sites to minimize exposure to worst or most difficult to shield secondary radiation
- Deep dielectric discharging represents a hazardous process at the Moon's surface and likely an agent for regolith gardening during large SEP events → PSRs near poles are regions prone to DDD as process depends critically on regolith temperature; not a likely issue at low latitude (< 80 degrees)

Back up and Additional Information of Potential Relevance

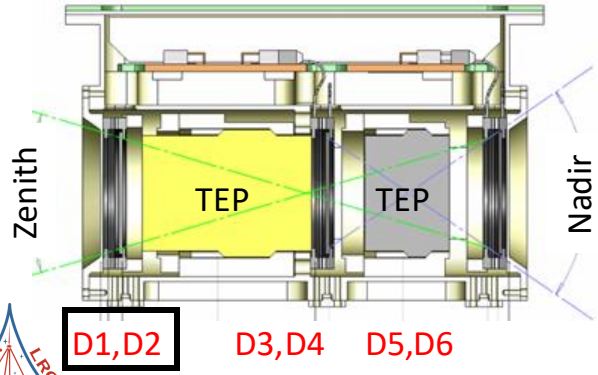
CRaTER Performance Specifications

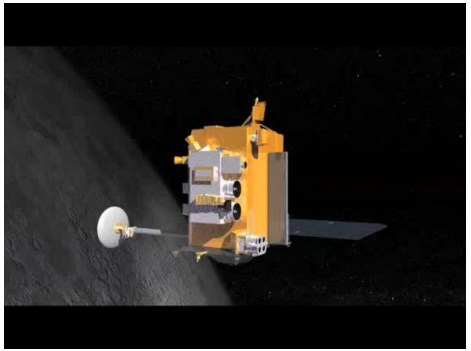
CRaTER's design has thick/thin detector pairs at 3 points through TEP:

- 3 "low LET" thick detectors (D2,D4,D6)
- 3 "high LET" thin detectors (D1,D3,D5)
- **Energy resolution <0.5%** (at max energy); GF ~1 cm^2-sr (typical)

This corresponds to:

- LET from <**0.2 keV/μ to 2 MeV/μ**
- Excellent spectral overlap in the **100 kev/μ** range (key range for RBEs)
- 100 kbps data rate – telemeter every pulse height in all six detectors whenever any one detector passes its detection threshold (i.e., no in-flight coincidence logic required, typical of similar sort of instruments)



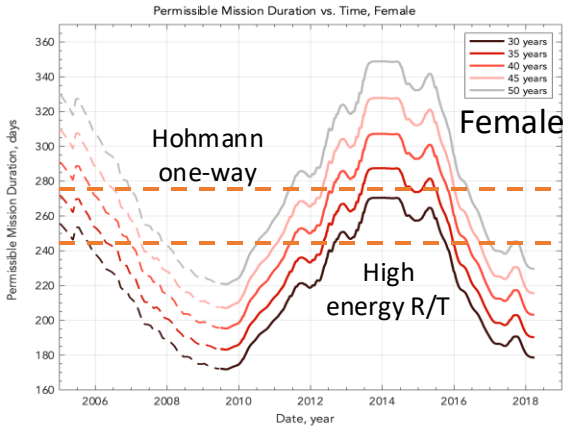


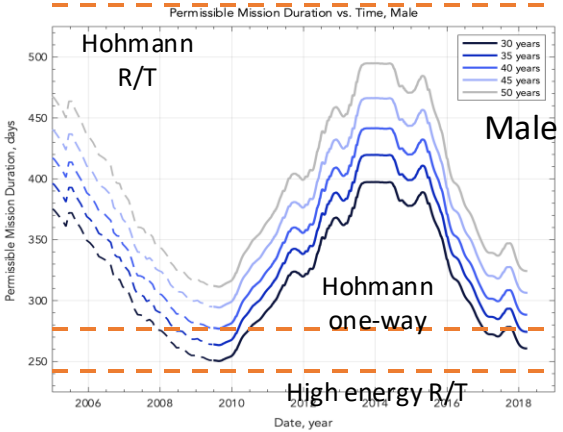
Vignette #4.

CRaTER Observations and Permissible Mission Duration (PMD) for Human Operations in Deep Space

- Wouter C. de Wet (UNH → now ORNL) lead

PMD: Moon versus Mars





(de Wet et al., 2020)

- Lunar Gateway: ~ 30 day missions (per mission, well below PMD)
  - At solar min → ~7 (10) missions per female (male) astronaut
  - At solar max → ~ ~11 (16) “ ”
- Mars: Assume Hohmann transfer orbit….
  - ~9 months (~275 days) each way to/from Mars (total ~550 days)
    - One-way transit exceeds PMD for most females and only few males depending on phase; Round-trip transit >PMD for all
    - ~16 months for realignment plus transit (12,410 days!!); higher energy orbit solution?

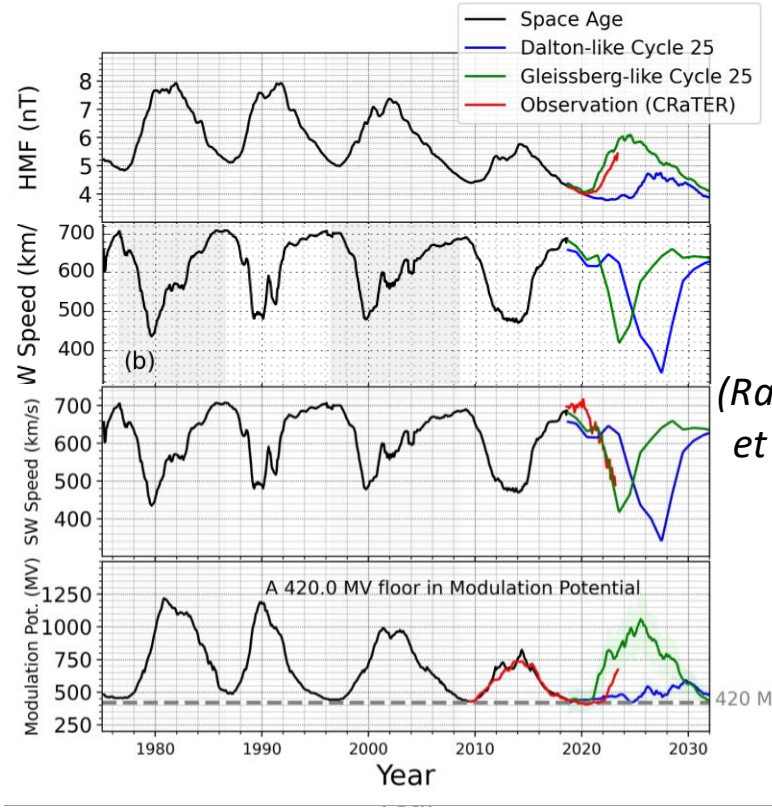
Vignette #5.

Characterization of the Space Radiation Environment Through a Modern Secular Minimum

- Fatemeh Rahmanifard (UNH) lead

“It's tough to make predictions, especially about the future” – Y. Berra

- LRO experienced Solar Cycle 24 (red curve)
- HMF and SW speed distribution weakest of Space Age; these control how much GCR makes it into solar system
- “Modulation Potential” is a quantitative measure of how effective GCRs are shielded by heliosphere
- Cycle 24 peak was ~750 MV (MegaVolts) compared to ~1200 MV in Cycles 21 and 22
- Unclear whether “floor” exists at 420 MV
- In 2019, predicted Cycle 25 would be either much like Cycle 23 (Gleissberg, green) or extremely low (Dalton, blue)
- In late 2023, it is somewhere between, more like Cycle 24 (red curve from 2019 to present)!



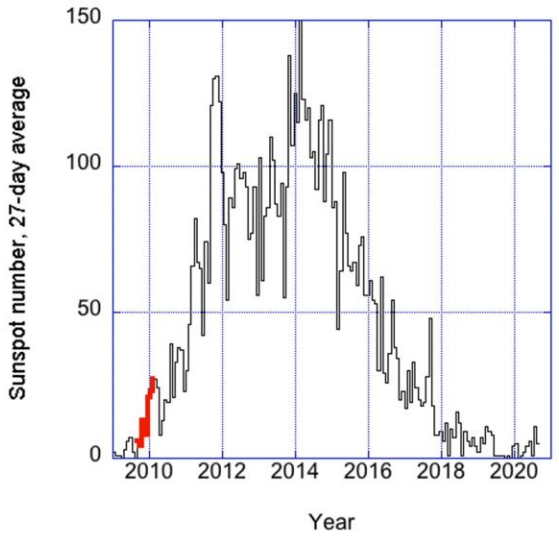
(Rahmanifard et al., 2019)

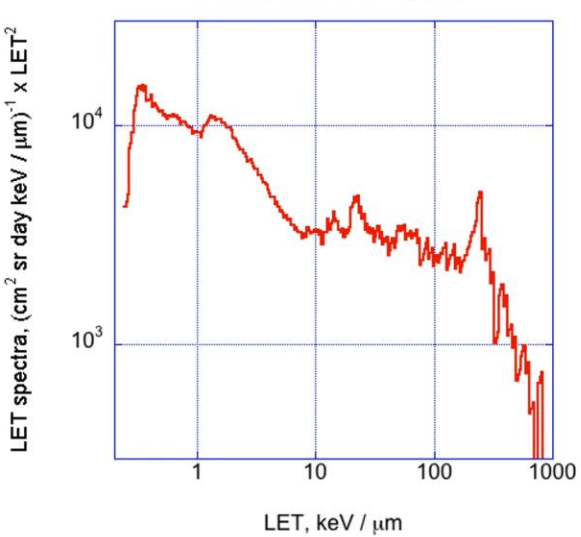
Where are we? No Time Like the Present!

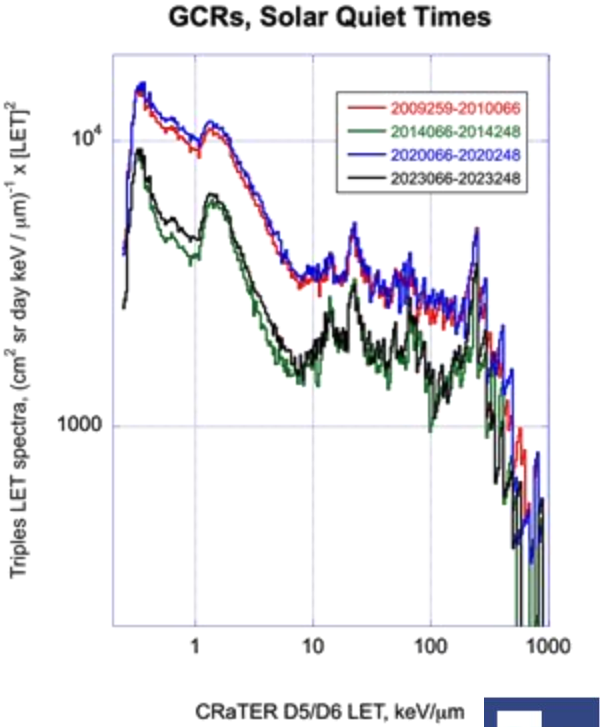
LET Spectra Measured by CRaTER Over a Full Solar Activity Cycle

Cosmic Ray Telescope for the Effects of Radiation

Aboard the Lunar Reconnaissance Orbiter

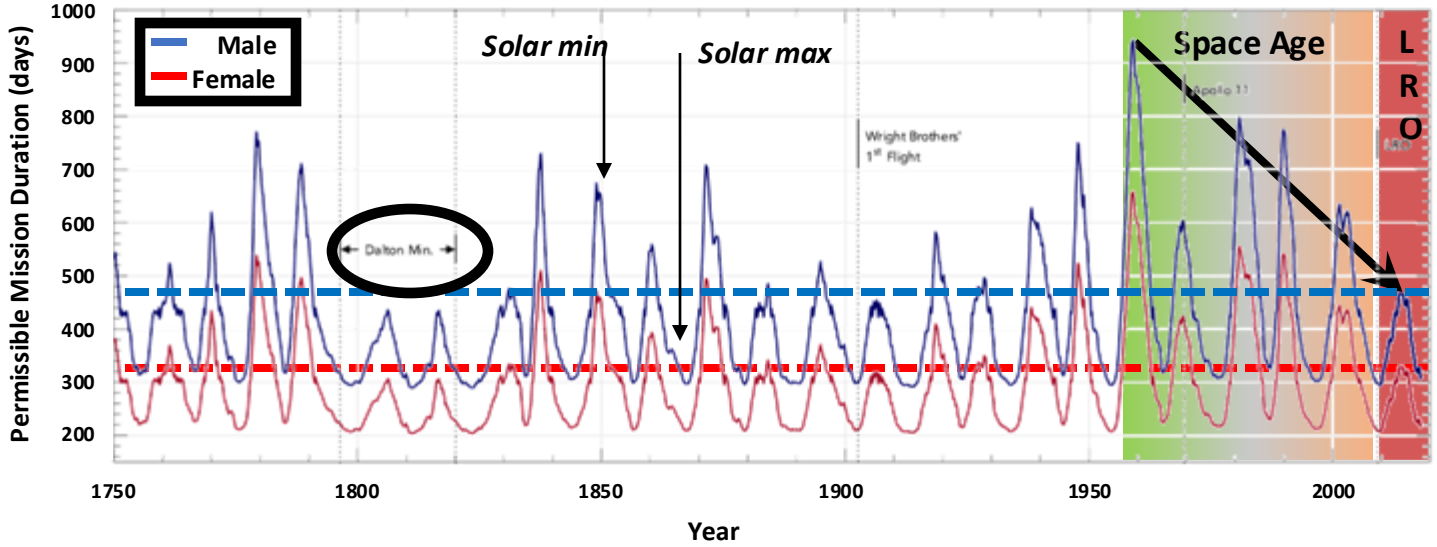






(Looper et al., 202X)

PMD Today and for a Quarter Millennium



- PMD for deep space conditions at 1 AU (L) from 1750 CE to 2018 CE (t) for 45-year-old (A) male (S, blue) and female (S, red) astronauts behind 20 g/cm^2 Al shielding (G)
- Current PMDs are as low as in recorded sunspot history with exception of “Dalton Minimum” (1790-1820)