Radiation Environments Beyond LEO

WRMISS, 2024

Boulder, CO

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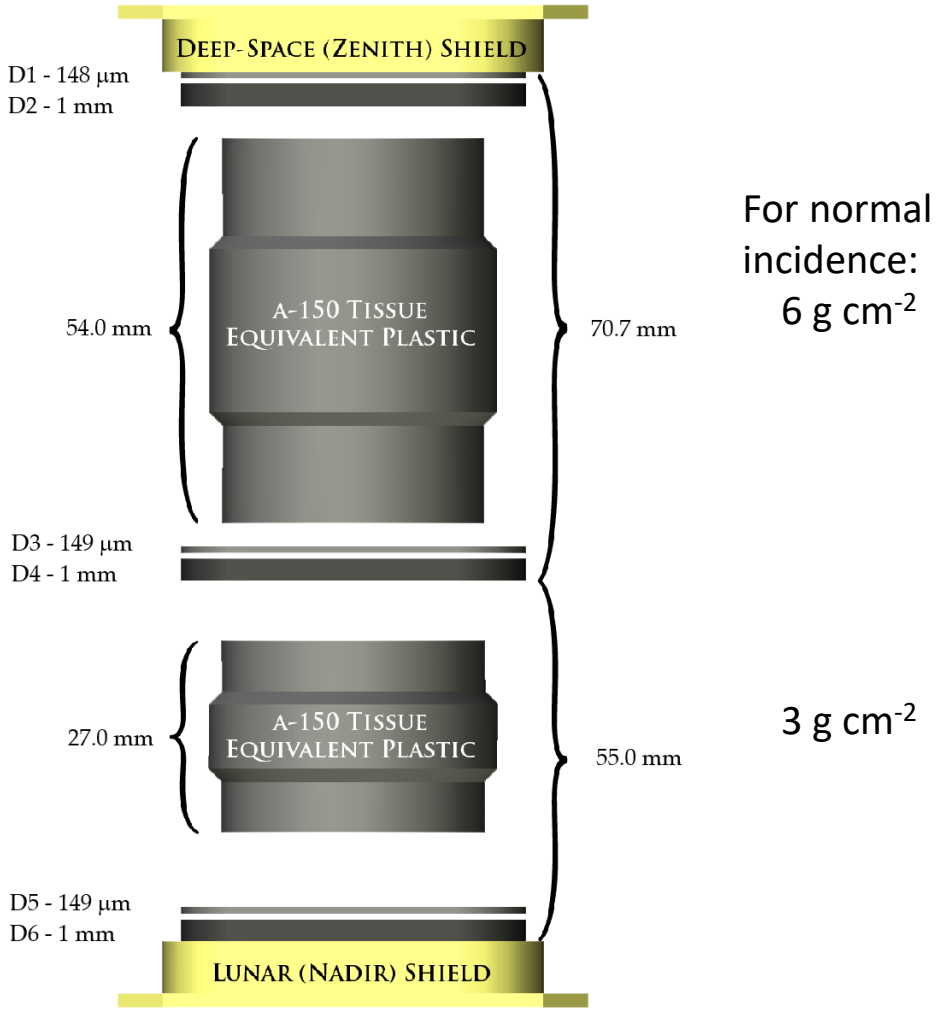
Radiation Measurements in Deep Space

- We have > 1 full solar cycle of data from MSL-RAD on the surface of Mars aboard Curiosity & from CRaTER on LRO in lunar orbit.
- MSL-RAD has operated on the surface of Mars since 2012.
- CRaTER has operated since 2009.
- GOES data from GEO available since the 1980s.
- Improved energetic particle detectors since GOES-16 (2018).
  - For operations, GEO ≈ deep space? Can GOES serve as alarm for lunar missions?

CRaTER on LRO

- CRaTER = Cosmic Ray Telescope for the Effects of Radiation
- LRO = Lunar Reconnaissance Orbiter
- CRaTER is LRO's "hood ornament," usually oriented to point zenith/nadir.
- PI Harlan Spence, UNH

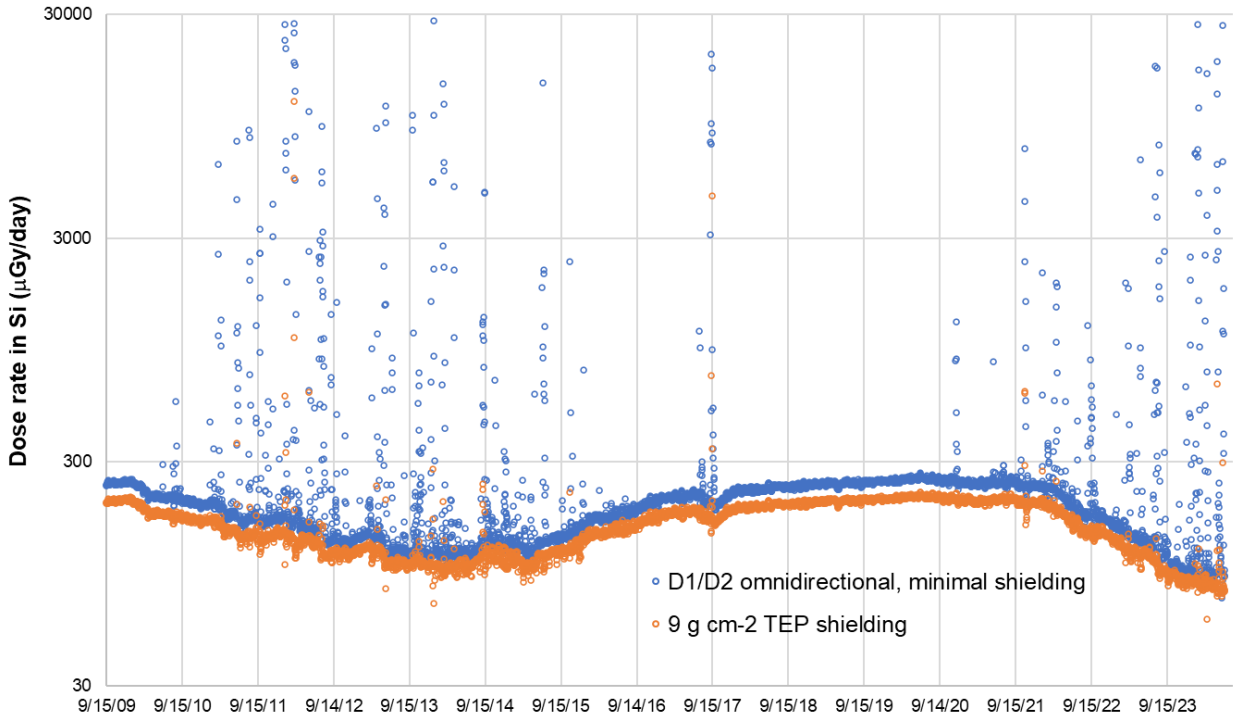


CRaTER Raw Data Products

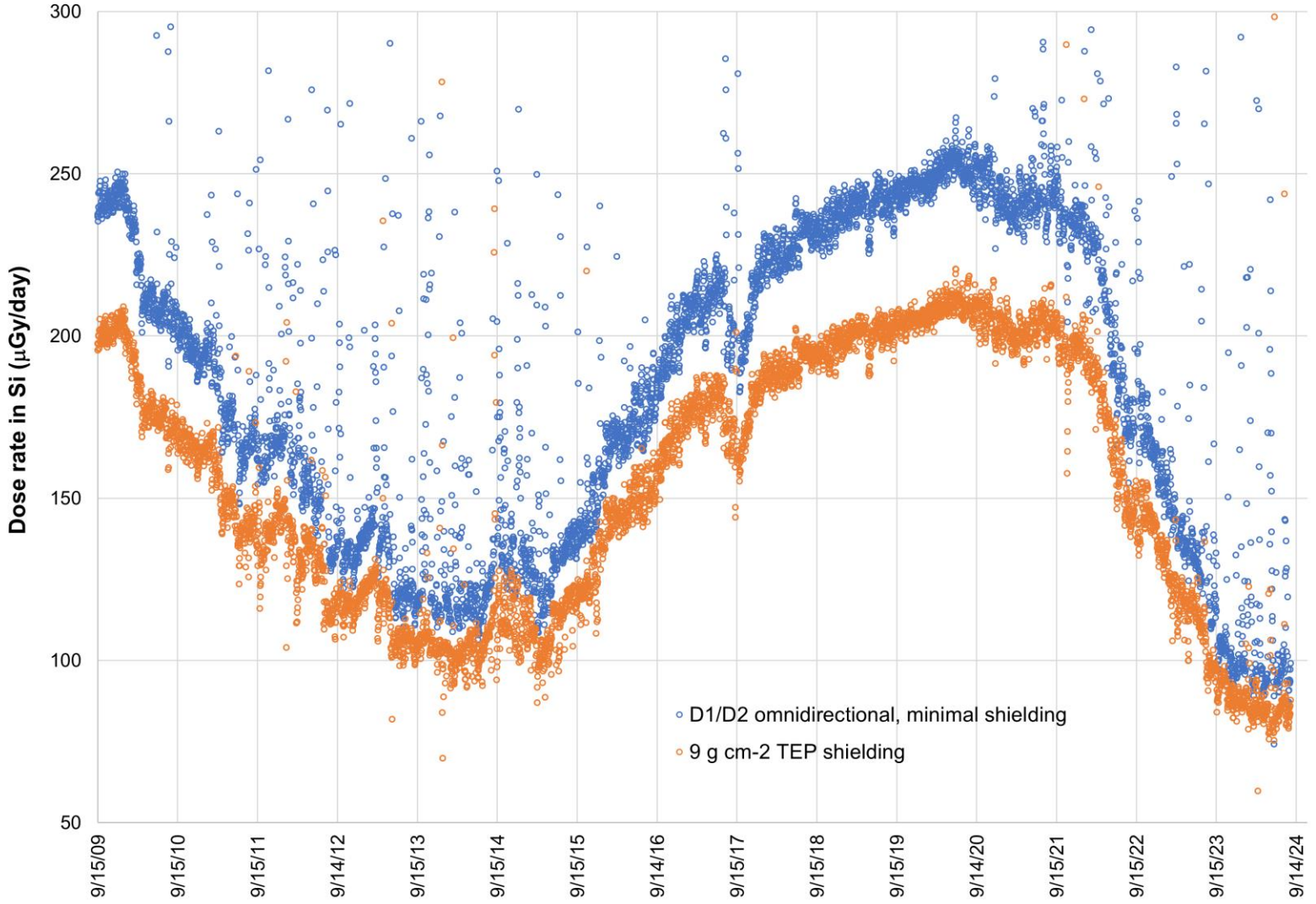
- Every digitized event is telemetered.
- Trigger is a hit in any of the 6 detectors.
- When environment is GCR or weak SPE, 100% of triggers are digitized & telemetered.
- Raw data can be used to generate absorbed dose rates, fluxes, LET spectra.
- Need to impose coincidence requirements for most analysis.

Absorbed Dose Rates From CRaTER Data

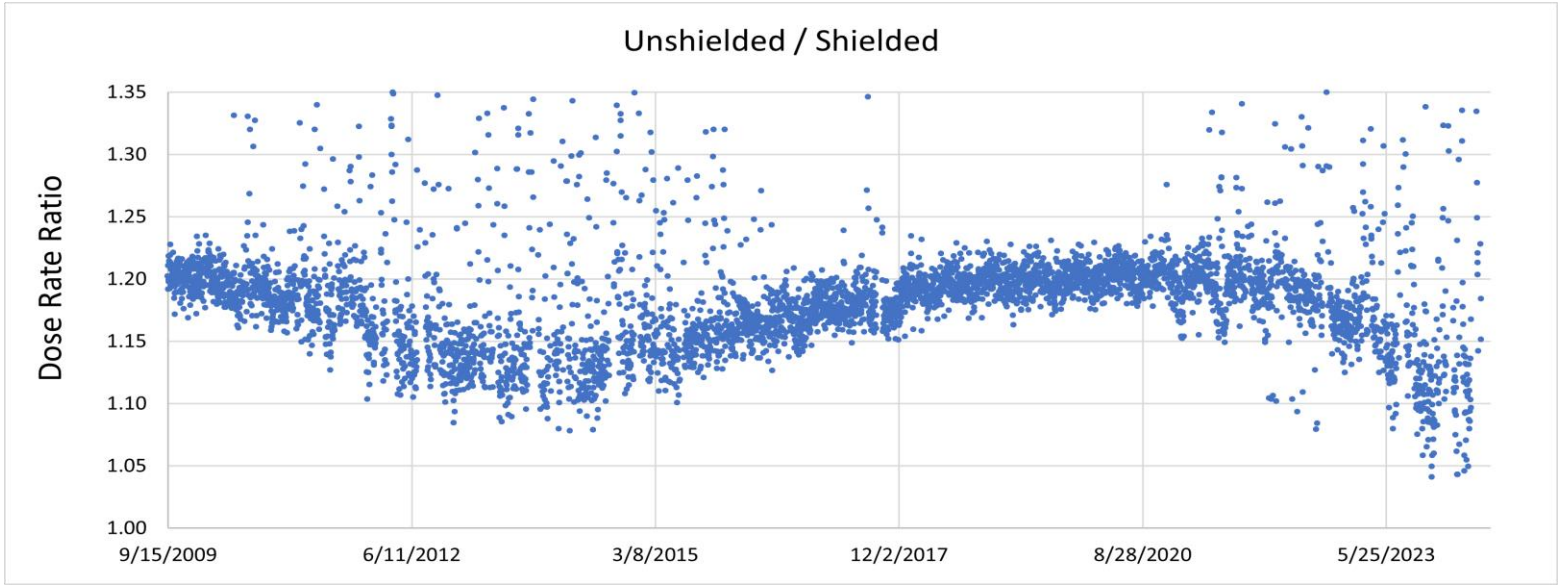
- D1, D3, D5 (300 μm) for high-LET ions.
- D2, D4, D6 (1 mm) used below ~ 50 keV/μm in water.
- 'Unshielded' → use D1/D2, no cuts.
  - Tricky part is to combine D1 and D2 doses without double-counting (detectors have overlapping sensitivity).
- Moon blocks ~1/3 of 4π, scale measurement down as if FOV = 2π.
- Use D2*D4*D6 coincidence events to calculate dose in the view cone & extrapolate to 2π geometry.
  - Shows effects of 9 g cm^{-2} TEP shielding on dose rates.



Zoom in on GCR

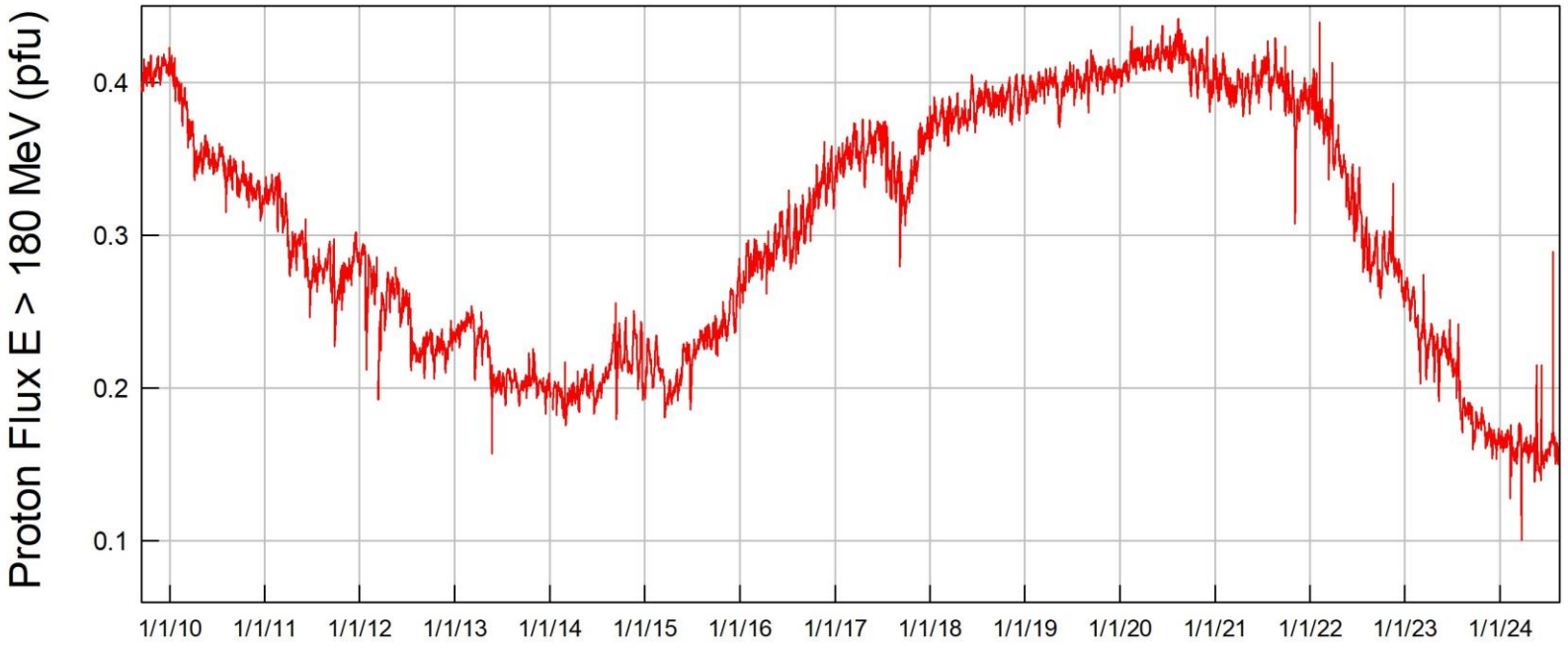


Absorbed Dose Rate Ratio, 2009-24



- Shielded = D2*D4*D6 coincidences, unshielded = D1 or D2 only.
- Ratio goes high during SPEs.
- Trend for GCRs clearly shows modulation. Ratio stays between 1.05 and 1.23.
  - Solar min: more low-energy GCRs present that can hit D1/D2 but cannot penetrate to D5/D6 → ratio is relatively large.
- Recent data show stronger solar max now than in Cycle 24.

CRaTER Integral Proton Flux Above 180 MeV

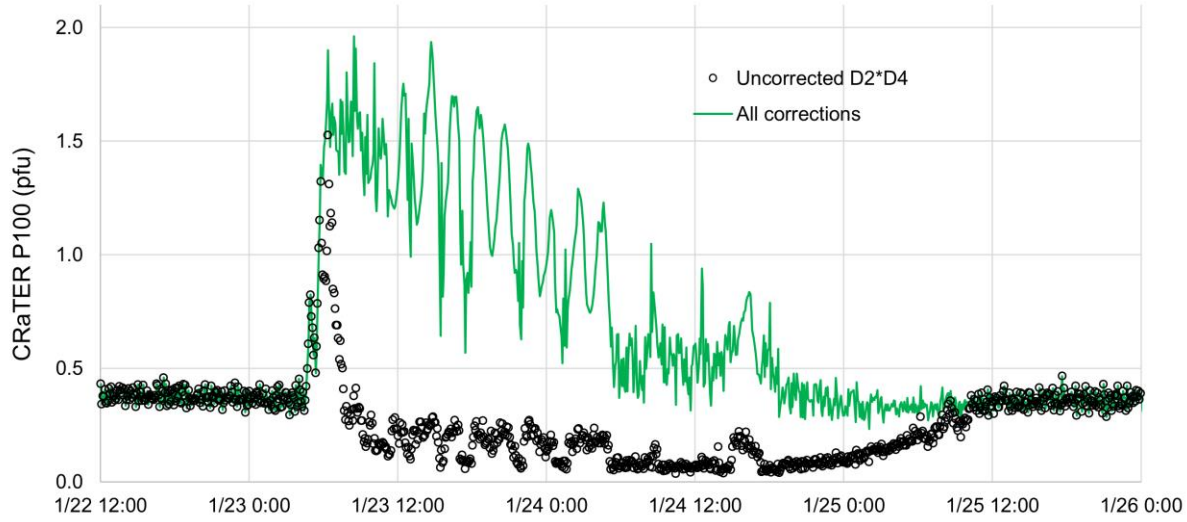


- dE/dx information from the thick detectors → straightforward to produce integral flux time series for protons and helium.
- Updated proton flux shown here, a few SPEs visible in recent data.

Extend Integral Flux Analysis to E > 100 MeV & Compare to GOES

- Can we use GOES as warning system for crew on lunar missions?
- GOES P100 = integral proton flux above 100 MeV → proton range > 10 g cm^{-2} Al
- Modify E > 180 MeV analysis to include E > 100 MeV.
  - D2*D4 instead of D2*D4*D6
  - Modify ΔE cuts.
  - Corrections needed for highest rates.
    - Trigger rate > 1270 Hz → lost events.
    - D2 autonomously disabled (rare).

January 2012 SPE

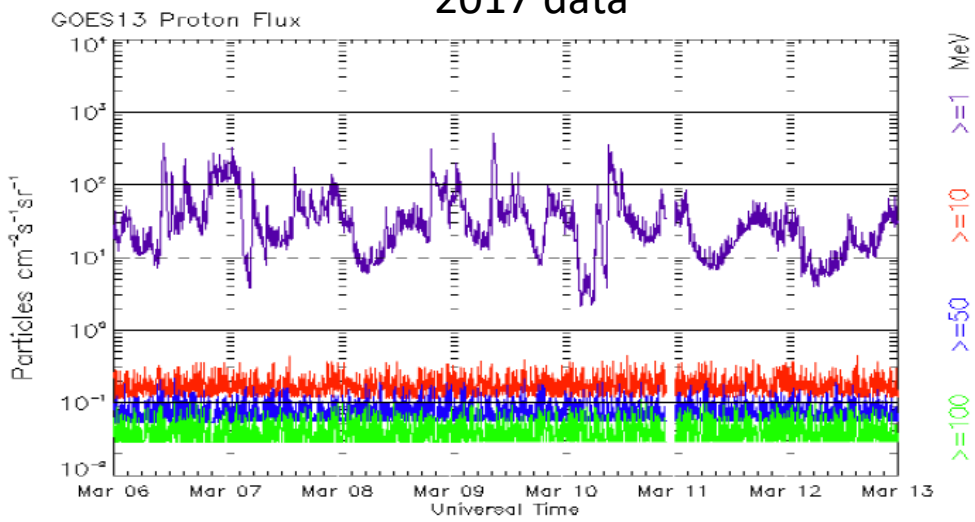


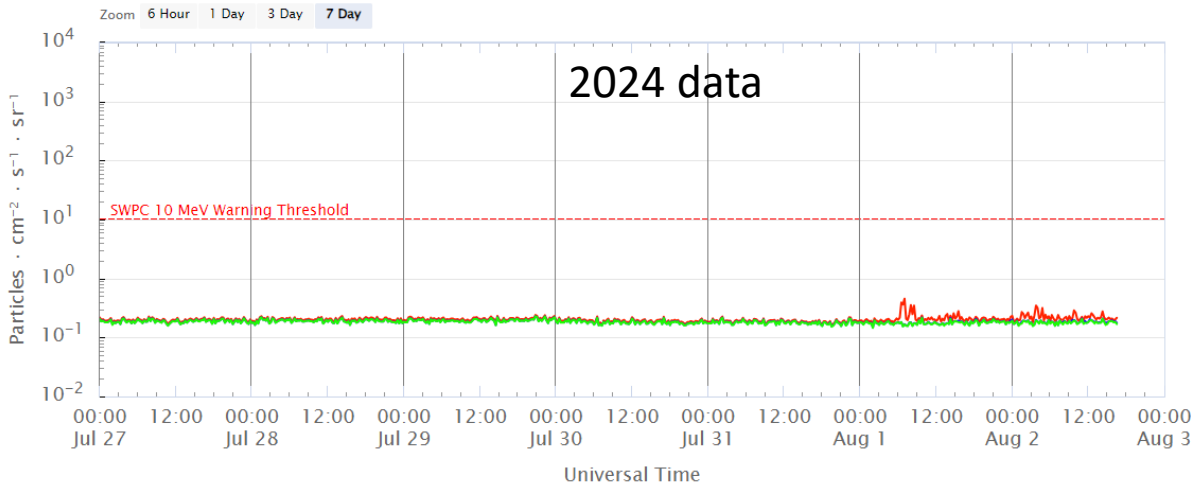
Oscillations are orbit-related.

GOES P100 – Issues in Older Data

- Prior to GOES-16, the P100 data product was made by combining EPEAD differential fluxes and HEPAD integral flux data.
  - HEPAD normalization is ???
- P100 low during solar quiet time.
- The energetic particle instrument suite was updated starting with GOES-16 (2018).
  - Space Env In-Situ Suite (SEISS)
  - Quiet time P100 now ~ 0.18 pfu, more in line with other data.
  - CRaTER P100 = (0.18 +- 0.2) pfu for the period shown.

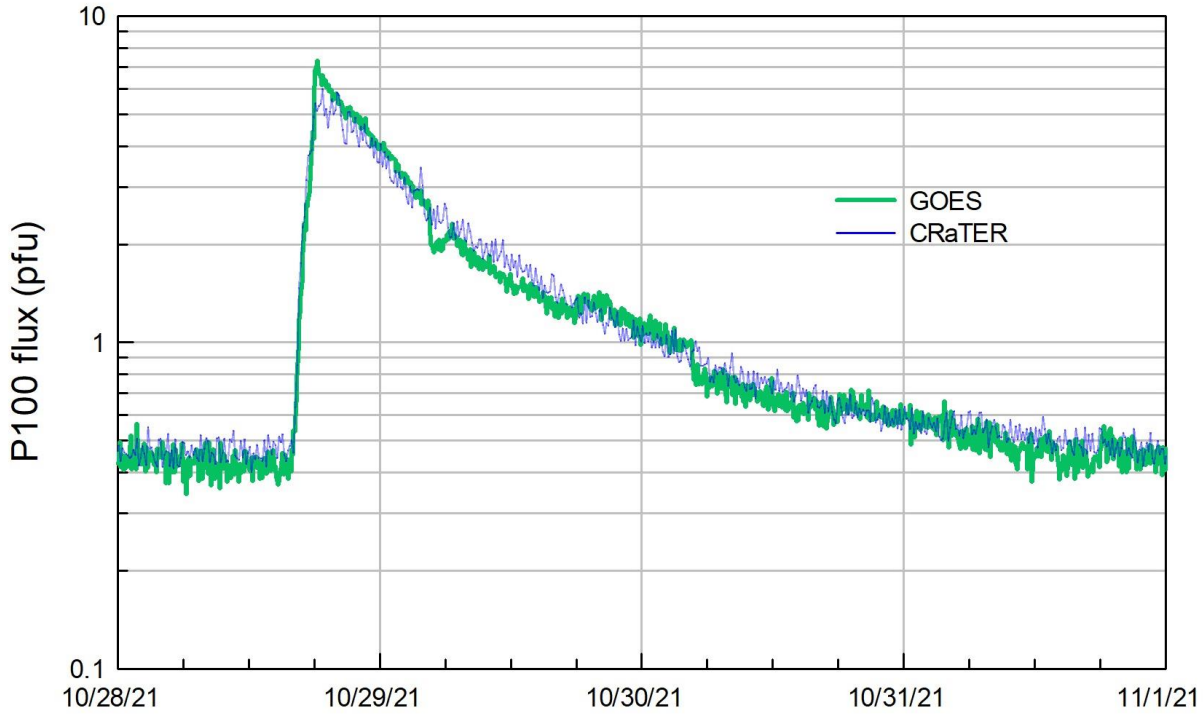
2017 data



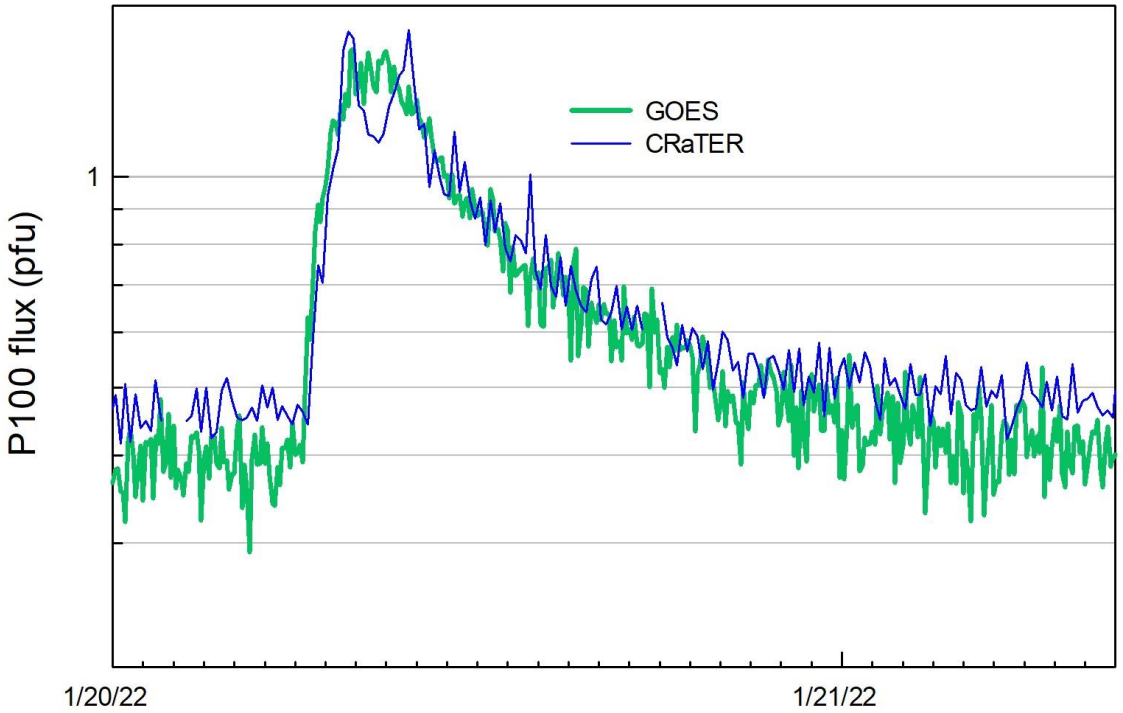


P100 > 1 pfu SPEs Since 2018

October 2021

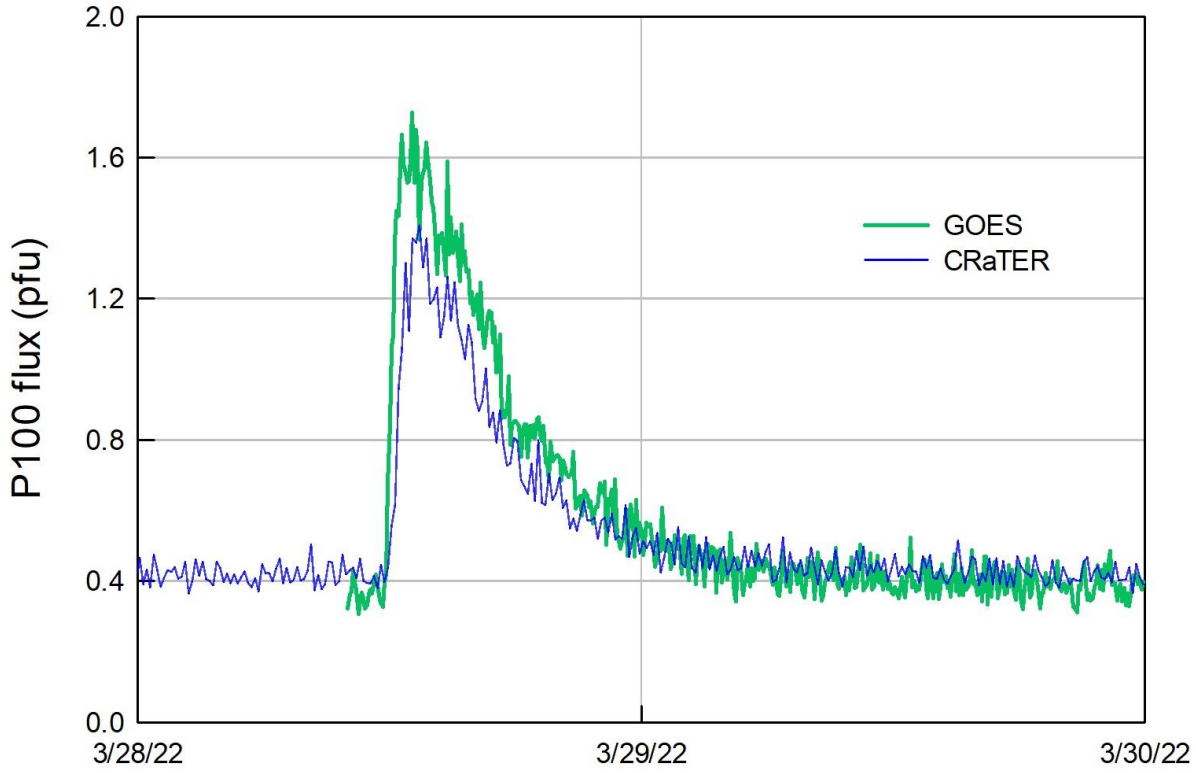


January 2022

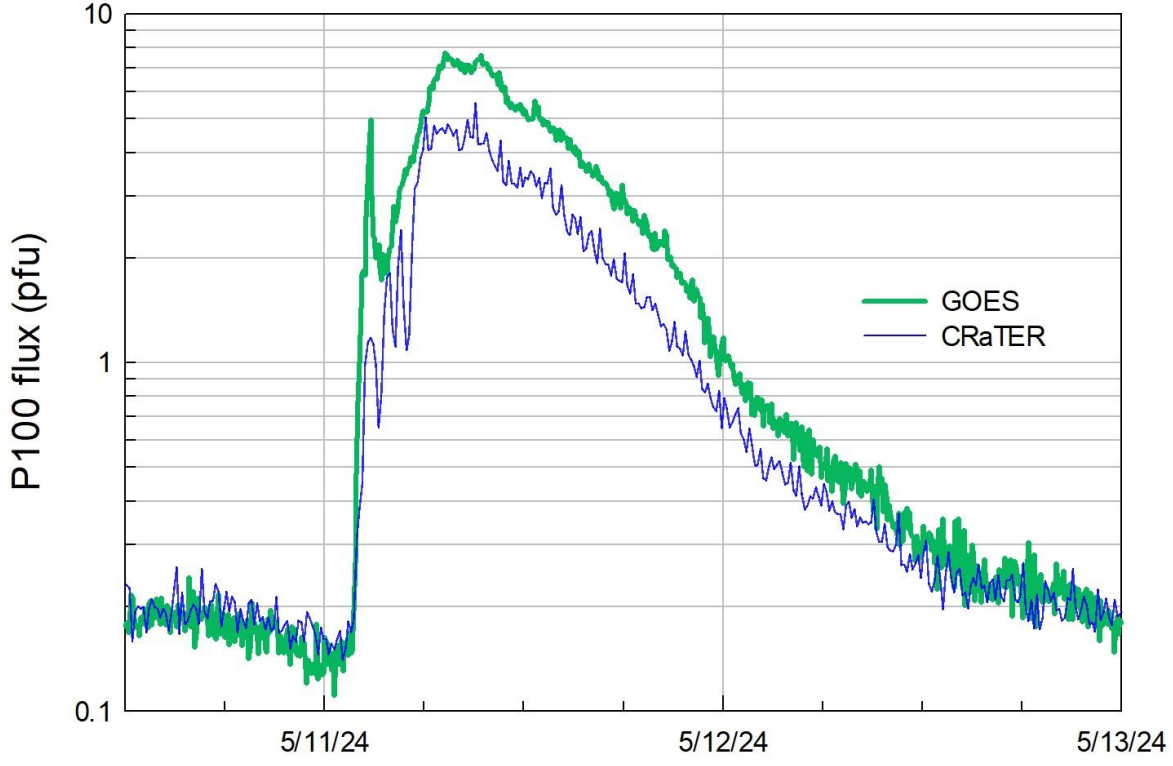


P100 > 1 pfu SPEs Since 2018

March 2022



May 2024



Oscillations & Flux Suppression

- Artifacts of the LRO orbit and the instrument FOV – geometric factor based on isotropic field is too large.
- Same effect seen in MARIE data from the Mars Odyssey orbiter.
- Anisotropic SPE (turning isotropic) as seen from an orbiting detector with a narrow FOV was modeled by Luhmann et al.
  - doi:10.1029/2006JE002886

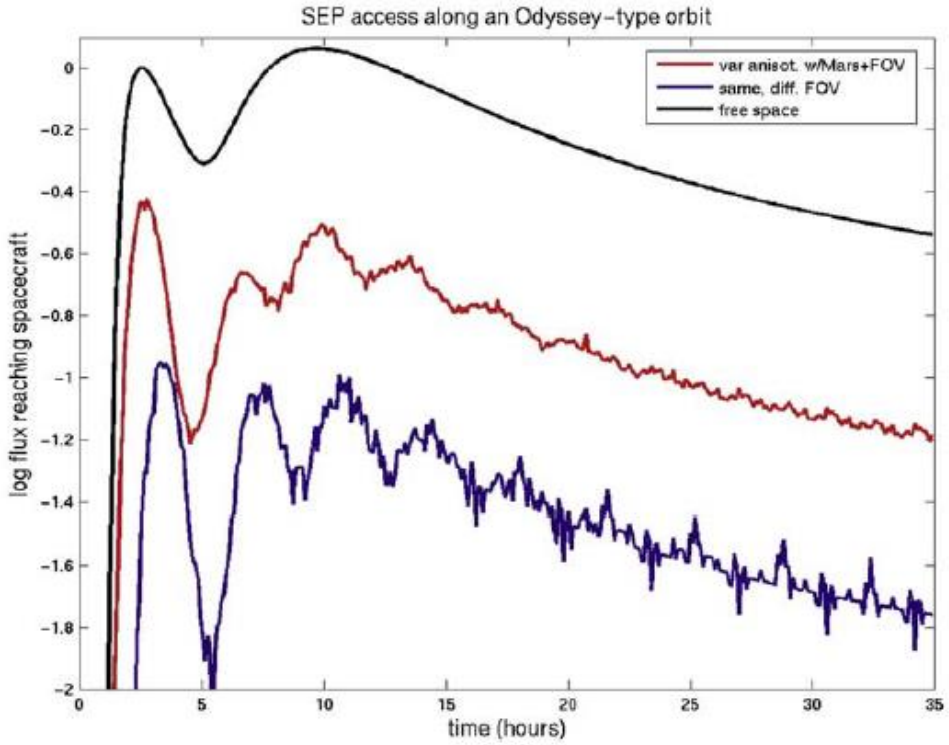
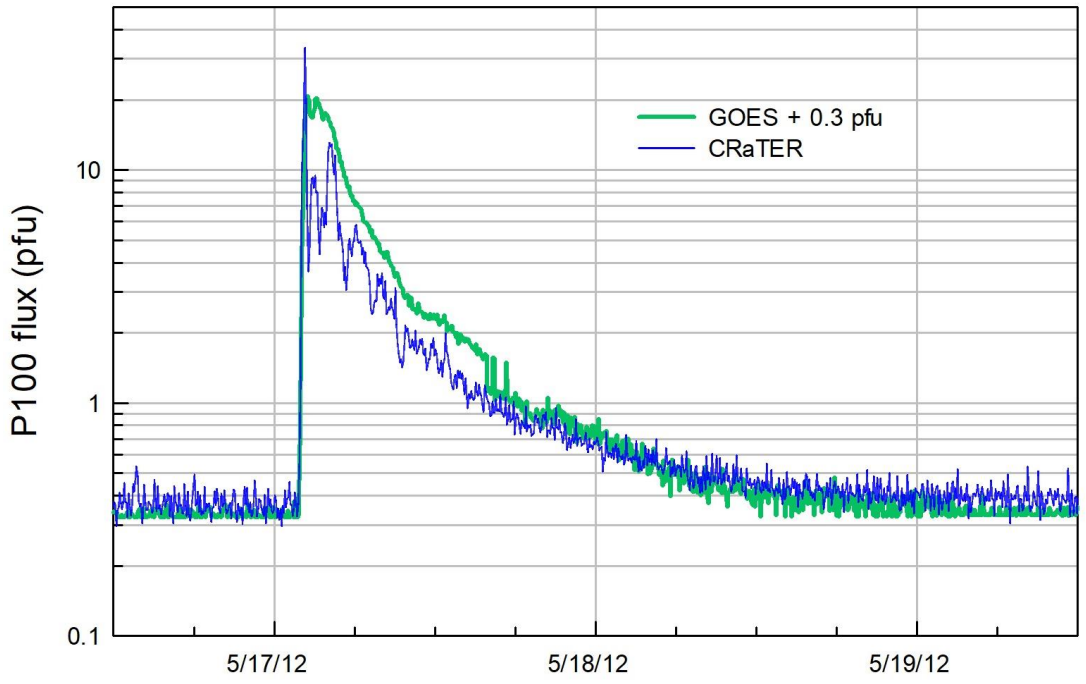


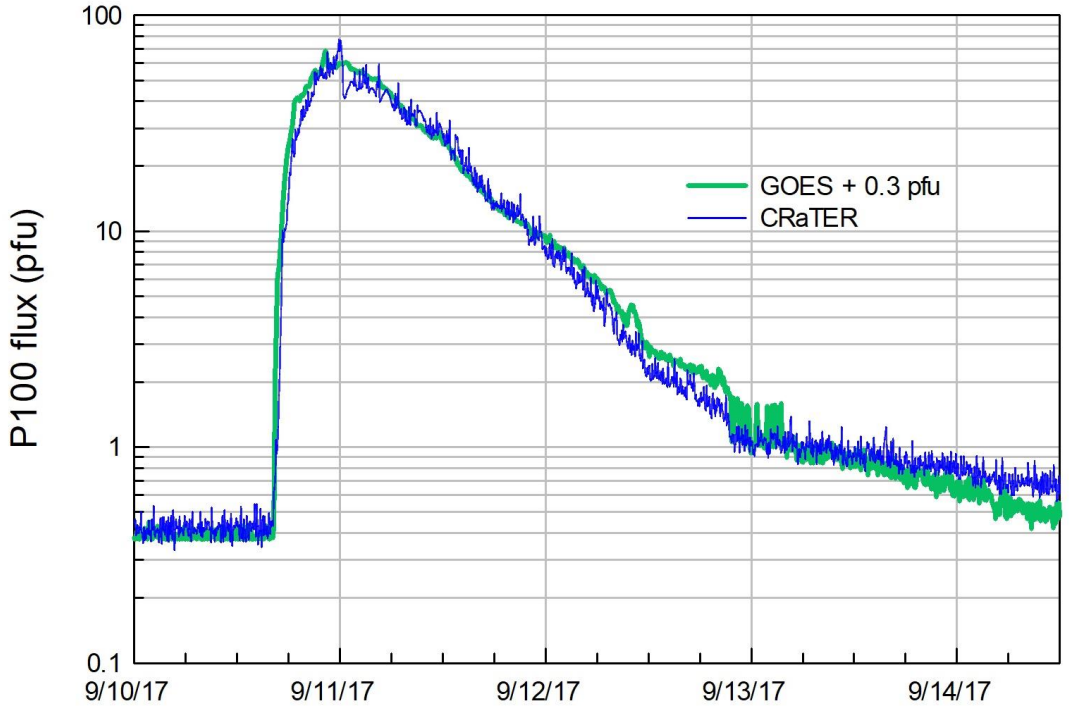
Figure 8. Same as Figure 7 but with an anisotropy that decays on the timescale of a day, and for fields of view with cones of acceptance of 60 degrees (red line, similar to MARIE) and 30 degrees (blue line). The noisiness of the simulated events results from the statistics of the test particle calculation and the impact of factors such as gyrophase.

Earlier Events

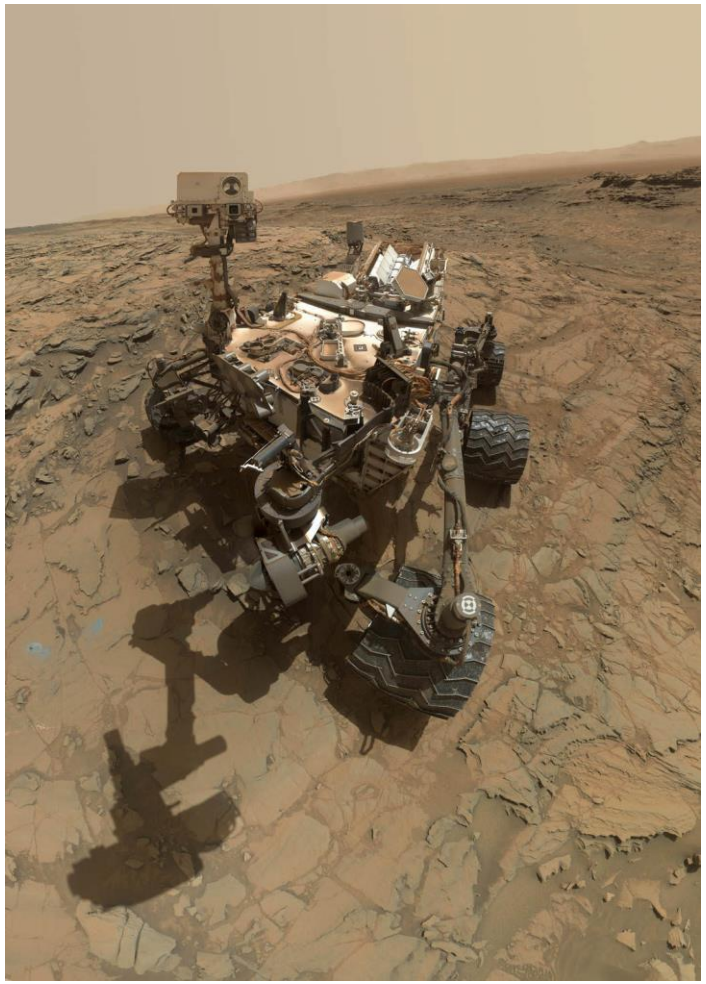
May 2012 GLE

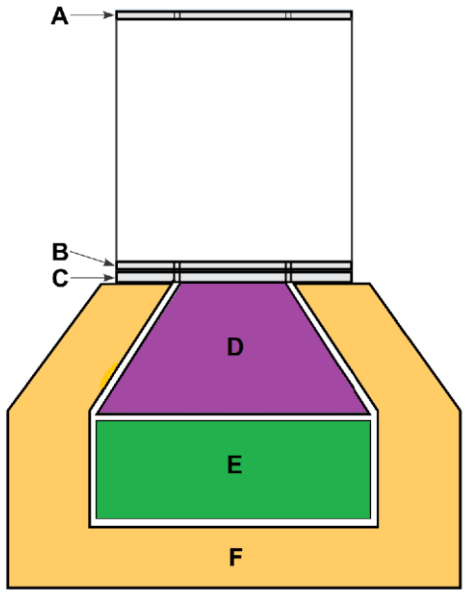


September 2017 GLE

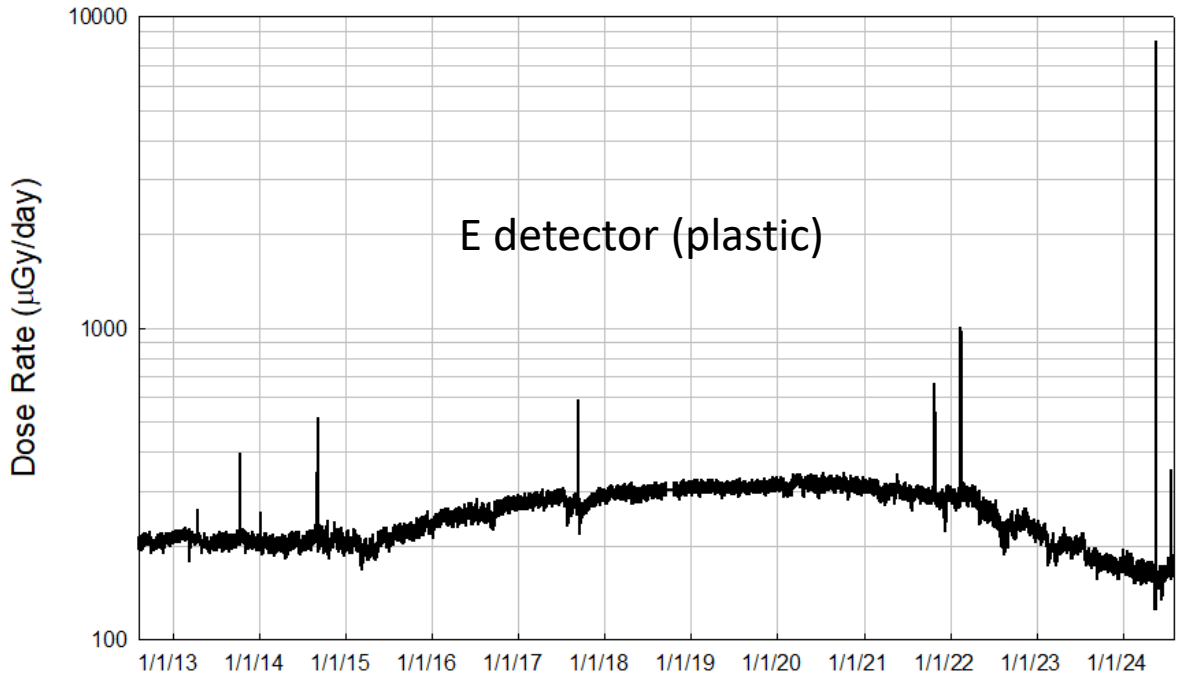


MSL-RAD



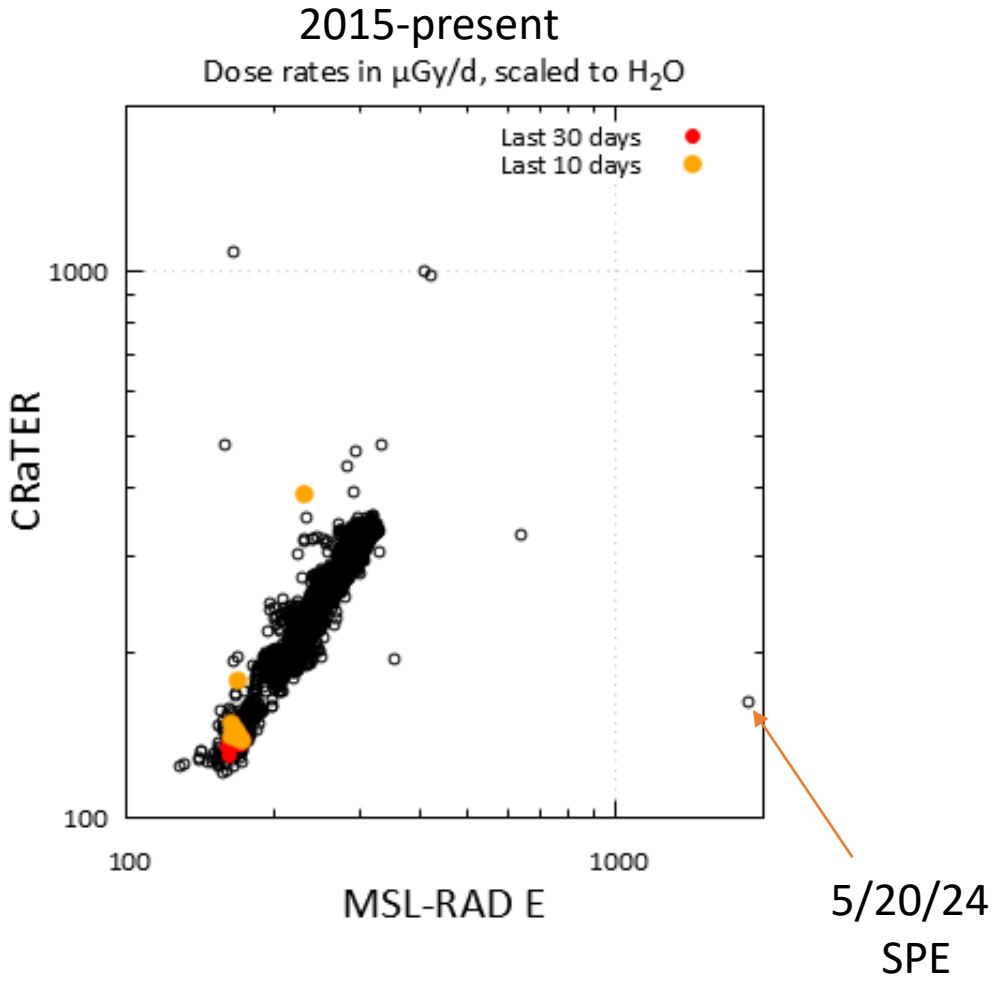


- PI Don Hassler, SwRI Boulder
- Curiosity still roving, 12+ years on Mars.
- RAD still 100% functional. Largest SPE so far seen on 5/20/24.



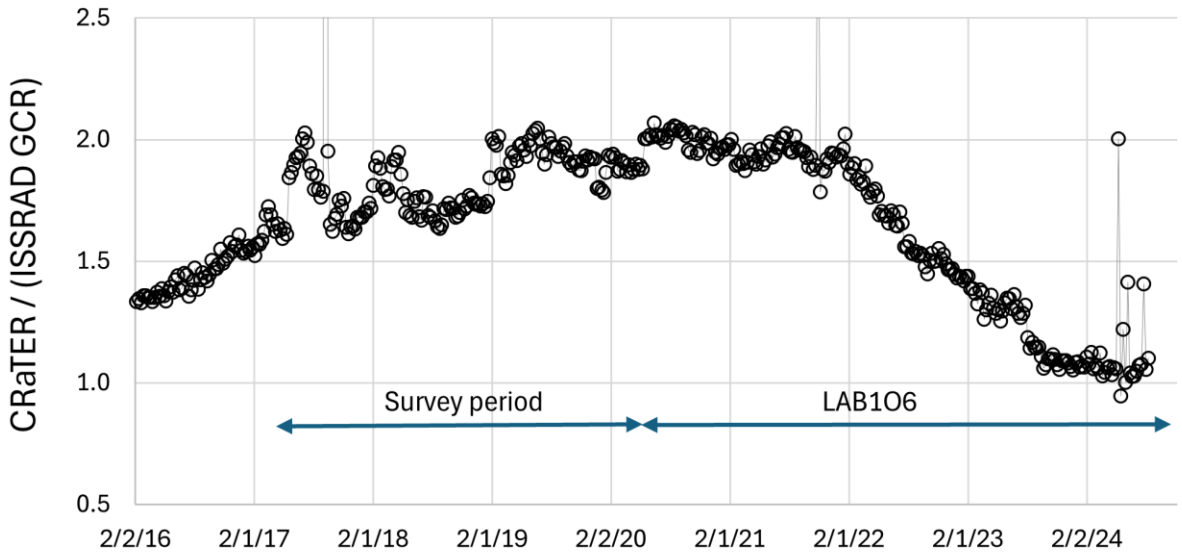
CRaTER vs. MSL-RAD Absorbed Dose Rates

- In solar quiet time, dose rates are strongly correlated as expected.
  - GCR at 1.5 AU ≈ GCR at 1.0 AU
- SPEs can be seen in one place or the other, sometimes both.
- When SEPs reach both, typically see higher rates in CRaTER due to radial gradient (~ $1/r^4$) and less shielding (9 g cm^{-2} vs. ~ 21 g cm^{-2}).
- Plotted CRaTER dose rate is under shielding.
  - D2*D4*D6 events extrapolated to 2π.



CRaTER vs. GCR Measured on ISS

- Weekly average ratio of absorbed doses in CRaTER and ISS-RAD shows effects of solar modulation.
- ISS-RAD history:
  - LAB1O3 for first year (ACO)
  - Survey for ~ 3 years 2/17 to 5/20
  - Parked @ LAB1O6 since May 2020
- GCR in LEO ≈ GCR outside LEO at solar max (geomag field ≈ IMF).
  - Factor of ~ 2 difference at solar min.



Conclusions

- CRaTER and MSL-RAD both continue to provide useful data into their second solar cycle of observations.
- Long-term measurements at Moon & Mars provide bounds on likely crew exposures for future missions.
  - GCR modulation shows up in many ways.
- SEP events as seen in GEO and lunar orbit are similar if not identical.
  - Newer GOES energetic particle suite is much improved.
- GOES will provide an adequate warning system for lunar crews.

THANKS FOR YOUR ATTENTION!