Latest Results from the MSL-RAD Experiment

Cary Zeitlin on behalf of the MSL-RAD Science Team

MSL-RAD Science Team

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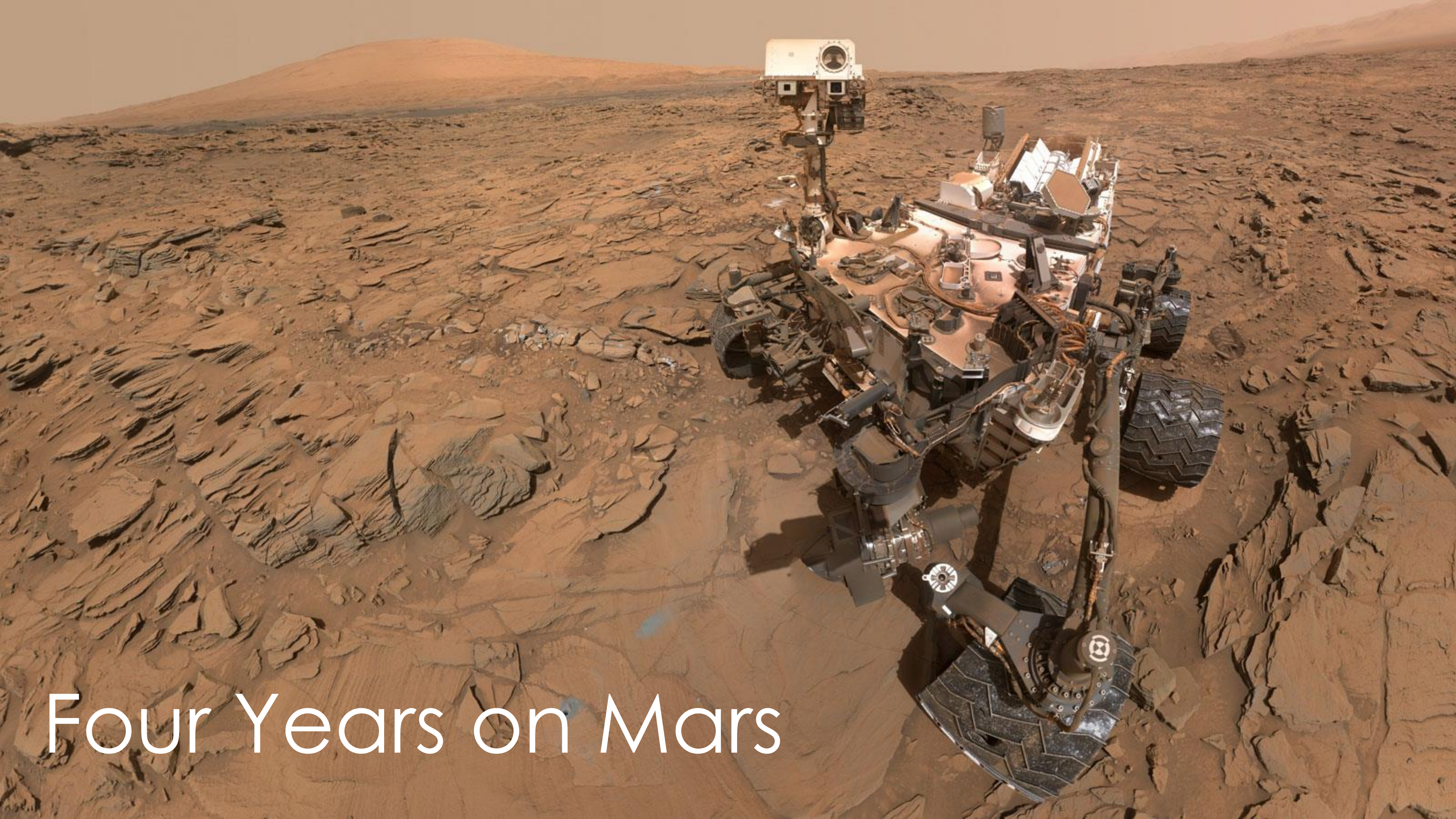
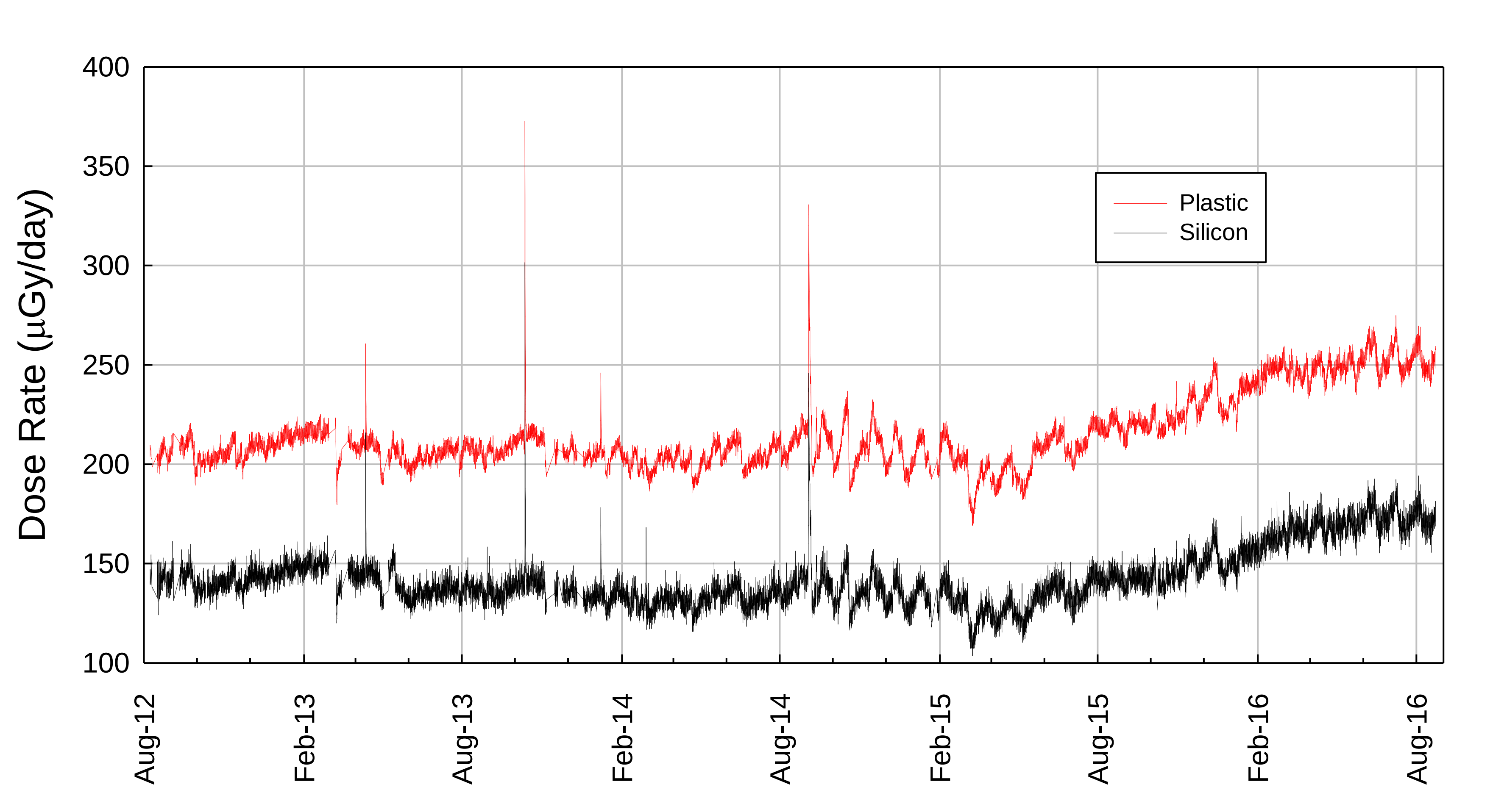

Four Years on Mars



Four Years of RAD Data

What's New with RAD

- Configuration changes:
  - Doubled RAD's data volume.
  - Updated Flight Software.
  - Tweaked calibration, dosimetry slightly affected.
- Science Team:
  - Published charged particle flux results for cruise – Bent.
  - Bent and Jingnan updated analyses for Modeling Workshop – stopping and penetrating charged particle fluxes, neutron / γ inversion.
  - Jingnan has updated atmospheric shielding studies.
  - Many model results from Workshop, Daniel will present.
  - Comparisons with data from other flight instruments.
  - Angular dependence – R. Wimmer, CAU Kiel
  - Co-rotating Interaction Regions – H. Lohf, CAU Kiel
  - Albedo proton study – J. Appel, CAU Kiel

Flight Software Updates

- Add dedicated counter for “No Readout” events.
  - Obscure but important, has factor of ~ 2 effect on normalization in previous neutron analysis.
- Increase # of histogram bins from 16 to 64 for B and E dosimetry.
  - Every energy deposit that contributes to the dose measurement in B or E is entered in the corresponding histogram, previously had only 16 bins in each so not very useful.

“No Readout” Triggers

- A “fast” trigger starts Level 2 processing.
- Three readout channels have fast triggers enabled:
  - BU = ultra-high-gain readout of B detector.
  - DH, one of 6 readout channels for the CsI.
  - EH, one of 6 readout channels for the plastic scintillator.
- Level 2 pattern matches depend on “slow” triggers:
  - For the scintillator triggers, we require 2-diode coincidences, e.g., DH*DI where DI is a readout channel connected to one of the other photodiodes mounted to D.
- We can have a fast trigger with no slow trigger.
  - Most common cause: γ-ray hitting scintillator readout diode.
  - No slow trigger ➔ event is not digitized.

Why It Matters

- RAD does not store all event records.
- Priority scheme for storage – Level 3 assigns 0, 1, 2, or 3.
  - Analyses that use event records require correction for “storage efficiency.”
    - All priority 2 & 3 events are stored, > 80% priority 1 stored.
  - Dosimetry-only and neutral particle events get priority 0, and only ~ 0.3% are stored (was ~ 0.1% earlier).
  - Correction = (pri0 events counted) / (pri0 events stored) according to initial assumptions. However, “events counted” includes “no readout” events → correction factor was overestimated.
  - Correct correction ~ factor of 2 lower.
- Our neutron spectrum paper suffered from this problem.

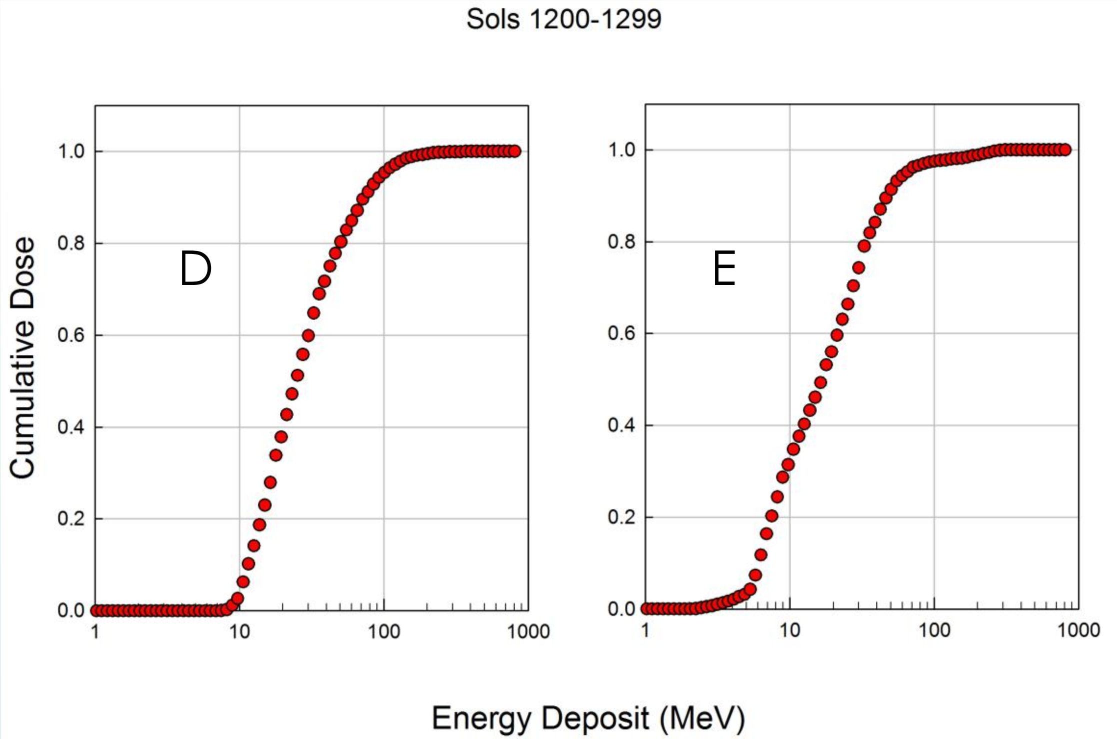
Revised Neutron Dosimetry Results

	Neutron Dose Rate (μGy/day)	Neutron Dose Equivalent Rate (μSv/day)
Kohler, Sol 1-194	14 ± 4	61 ± 15
New, Sol 1164-1224	4.9 ± 1.3	22 ± 4

- Changes in results roughly consistent with factor of ~ 2 from revised storage efficiency correction.
- Also roughly consistent with estimate from simple D and E dosimetry analysis.

Simple Dosimetry Using Onboard Neutral Histograms

- Use onboard neutral histograms rather than PHA event records.
- For workshop period, neutral dose rate in E averaged 5.9 μGy/day.
- D neutral dose rate averaged 7.5 μGy/day.
- Total = 13.4 μGy/day.
- Cumulative dose distributions shown for D and E.



Contributions to Neutral Dose Rates

	Dose rate (μGy/day)	Neutron Share	Neutron Dose Rate (μGy/day)
D	7.5	25%	1.9
E	5.9	90%	5.4
Total	13.4	54%	7.3

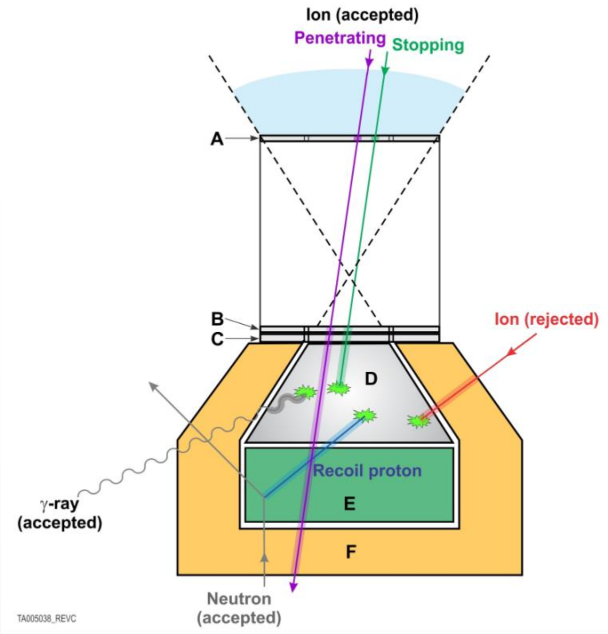
- Neutron shares approximated from Jan's GEANT4 simulations and the cumulative dose distributions.
- Very hand-waving but in reasonable agreement with new inversion result of 4.9 ± 1.3 μGy/day.

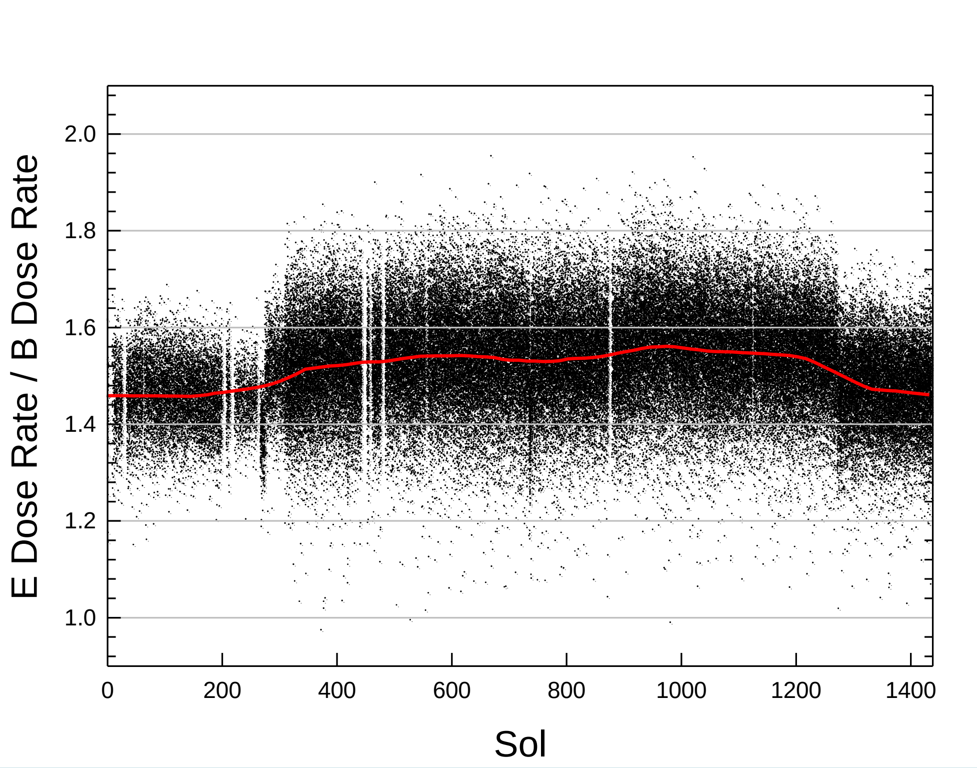
Calibration Tweaks

- Calibration last adjusted in Jan. 2012 during cruise to Mars, based on observed MIP peaks.
- Electronic gains are slightly temperature sensitive.
  - Temperatures in RAD were 28° C to 35° C during cruise, averaging 33° C.
  - On surface, range is 9° C to 39° C, average 18° C.
  - Onboard compensation tables not perfect.
- Careful study showed +2% change for BU, -5% for other B channels, net effect ~ +1%
- 3 of 4 E channels needed adjustment, net effect ~ -5%.

E/B Dose Rate Ratio

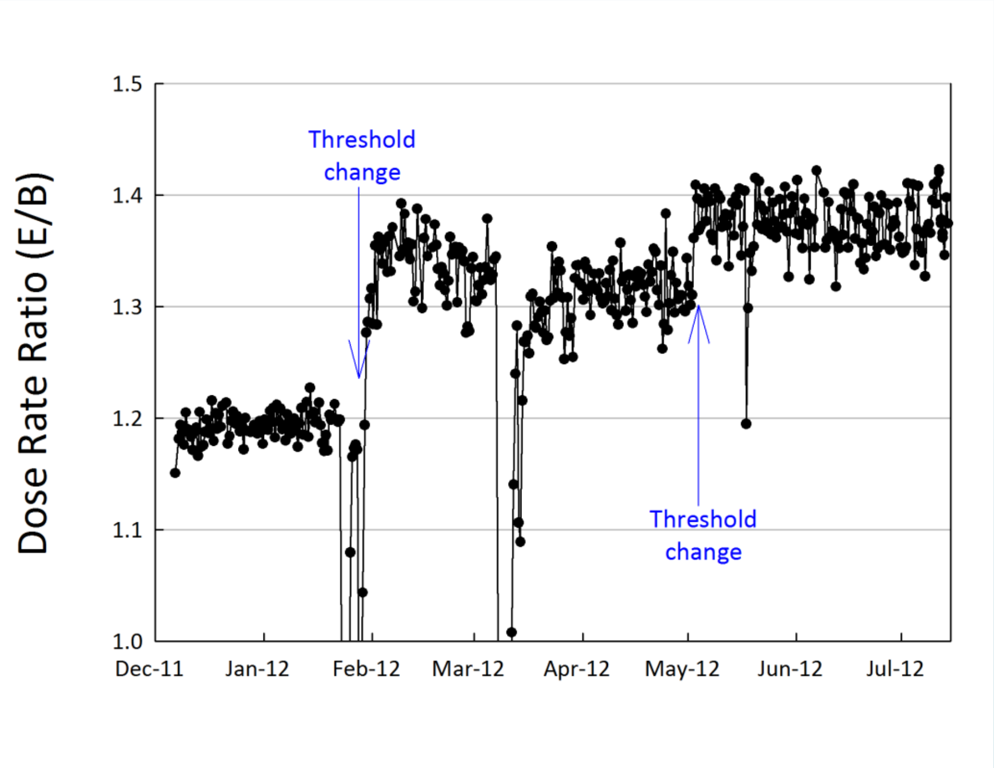
- Ratio approximates the "silicon to water" factor, but…
  - Plastic isn't water.
  - Sensitive to thresholds, calibration, environment.
  - On Mars, likely contribution from low-energy albedo protons that stop before B
    - Possibly sensitive to RTG background.
  - **Affected by nuclear interactions in the detectors, E includes fragments made in D.**





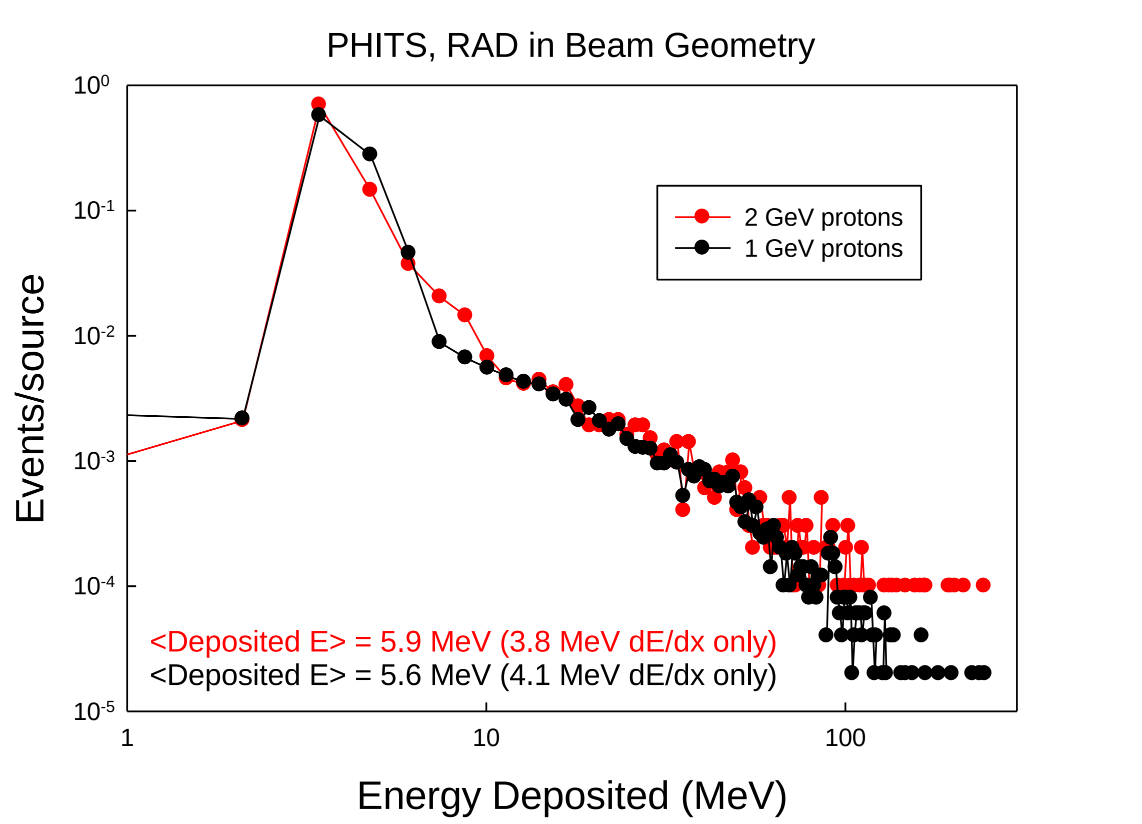
E/B Ratio Depends on Environment

- Easy to see in cruise data, where strong SEP events and Forbush decreases were seen.
- E/B ratio before the March 2012 event was higher than just after, with the same threshold.
- Increased modulation → lower ratio.



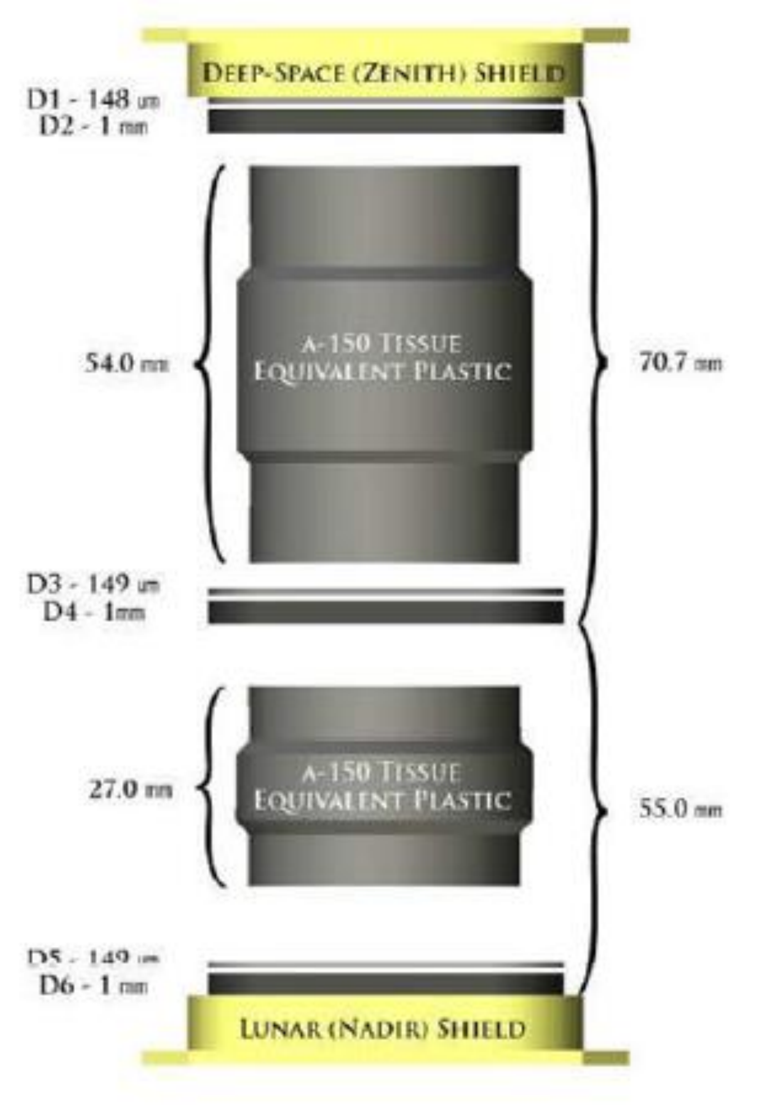
Effects of Nuclear Interactions in D & E

- Simple beamline geometry used in PHITS to shoot 1 GeV and 2 GeV protons at RAD.
- Some fragments may be coming from interactions in D.
- Average energy deposits pulled by tails, 40-50% higher than nominal dE/dx values.
- For Z ≥ 2 this may be balanced by fragmentation.
- Need to model full environment.



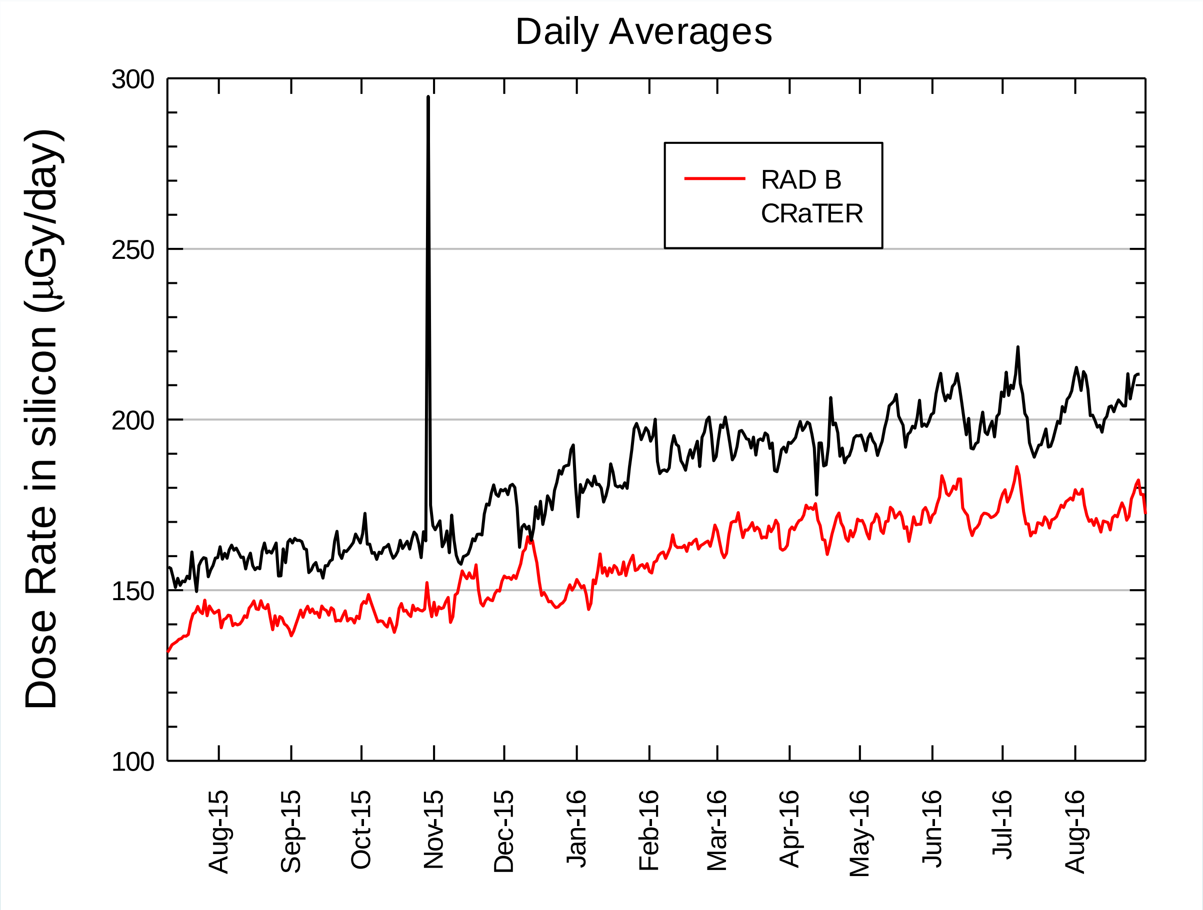
Comparison of MSL-RAD and CRaTER Dose Rates

- CRaTER = Cosmic Ray Telescope for the Effects of Radiation, flying in lunar orbit on LRO since 2009.
- Calculate "triples" dose rate = dose due to particles that create a 3-fold or higher coincidence in the stack (D2•D4•D6).
- Calculate dose in first detector pair for these events.



MSL-RAD vs. CRaTER Dose Rates in Silicon

- For MSL-RAD, 75 ± 10 μGy/d due to RTG, subtracted.
- RAD under ~ 21 g cm^{-2} CO_2.
- Last detector pair in CRaTER under 9 g cm^{-2} of A-150 TEP.
- For CRaTER, use telescope "triples" events, extrapolate to 2π geometry.
- Trends similar, but CRaTER dose rate higher.
  - Less shielded or some other normalization issue?



MSL-RAD vs. ISS-RAD
1 Feb – 31 Aug, 2016

Quantity	MSL-RAD	ISS-RAD
Flux from B dosimetry trigger (omnidirectional), pfu	0.41	0.45 GCR 2.45 SAA
Flux in A*B FOV, pfu	0.65	0.61 GCR 2.27 SAA
B dose rate (Si), μGy/day	170	192 total 145 GCR 1399 SAA
E dose rate, μGy/day	223	214 total 163 GCR 1529 SAA

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- ISS is less shadowed (33% of 4π blocked instead of 50%) but has geomagnetic shielding & maybe more bulk shielding.

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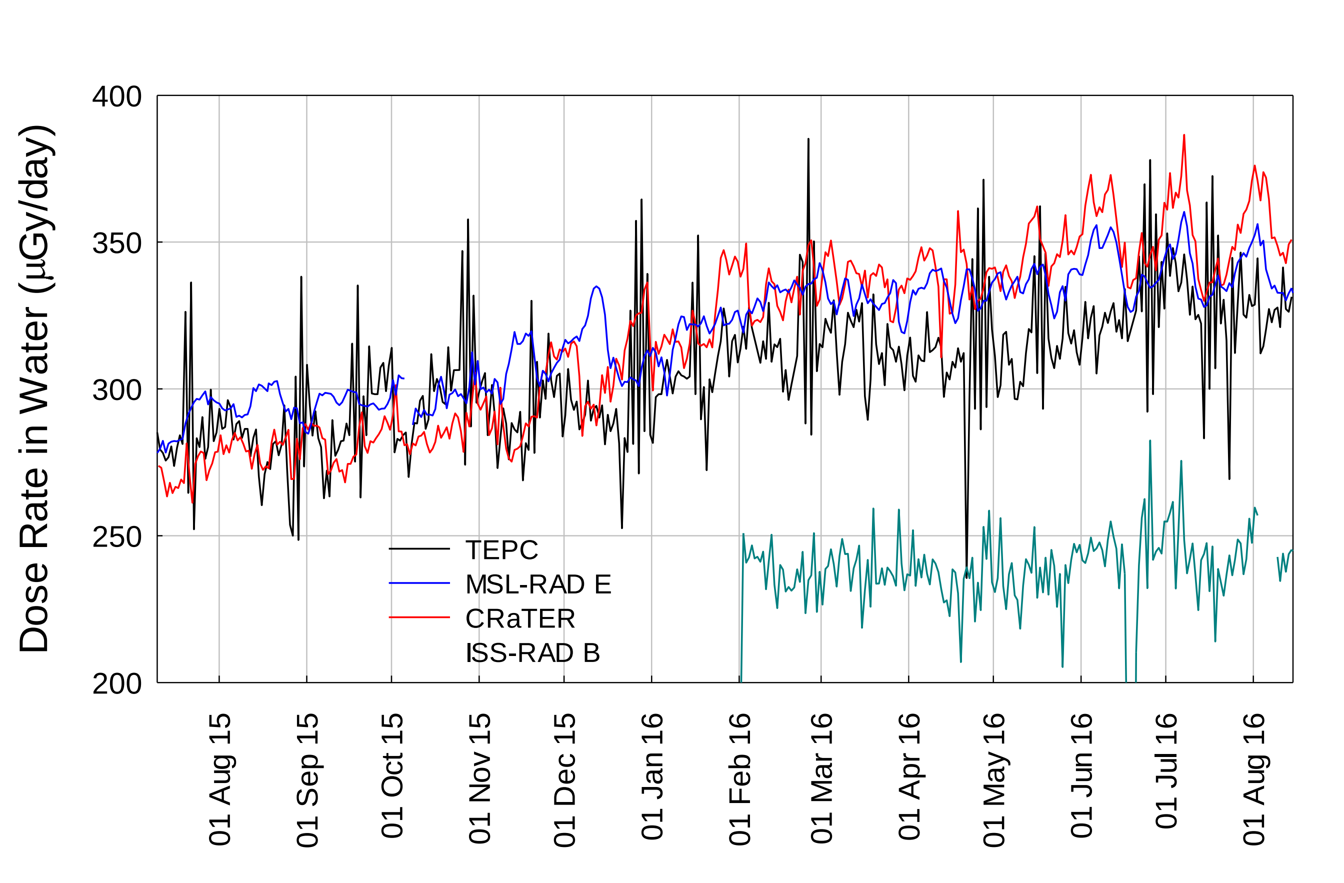
- Overall no help from the magnetosphere, at least for dose rates.

MSL-RAD + CRaTER + ISS Instruments

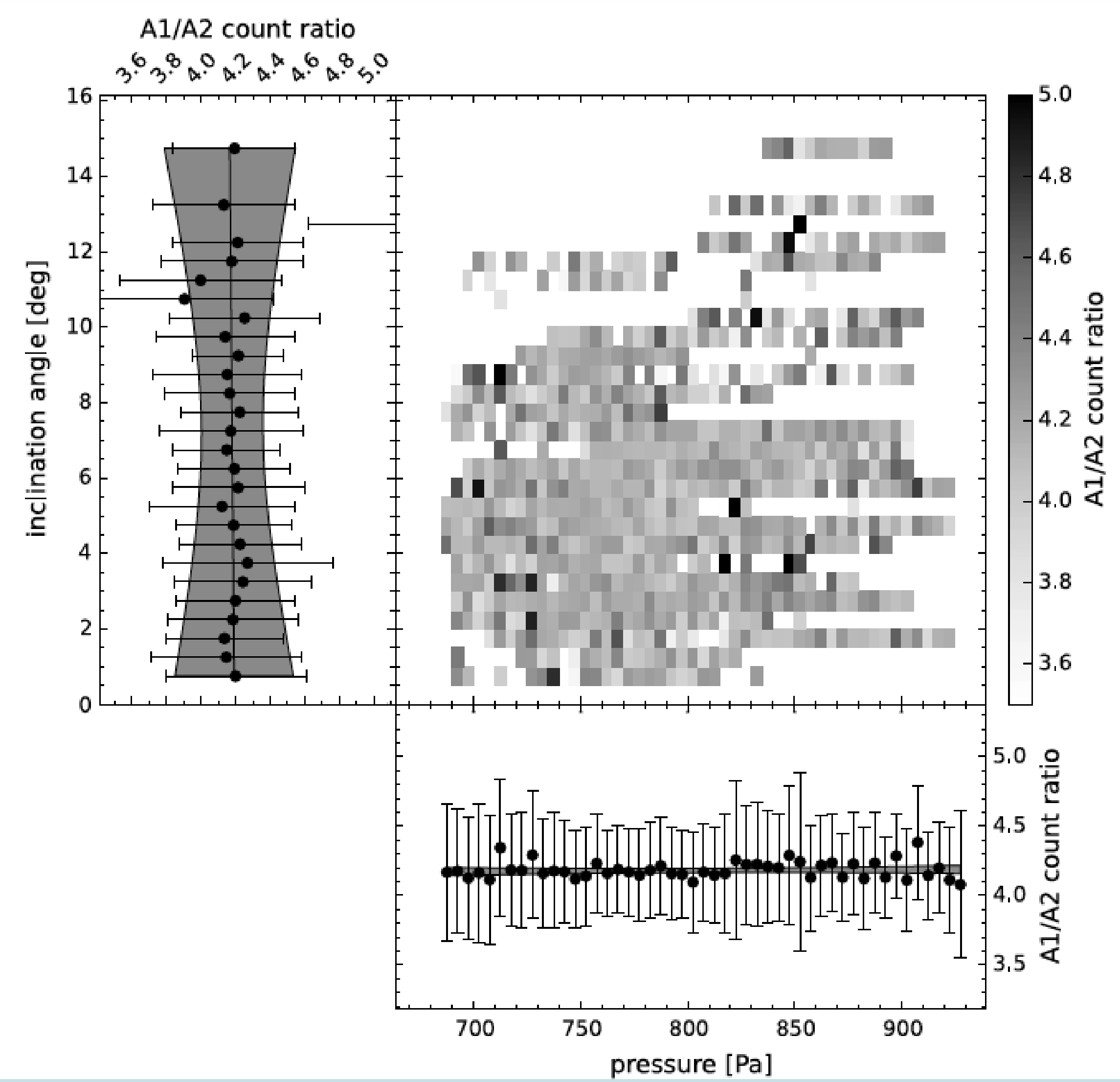
- Weakening solar modulation is letting in more low-energy ions.
- Sensitivity to these ions depends on shielding.
- From least to most shielded:
  - CRaTER
  - MSL-RAD
  - ISS-TEPC
  - ISS-RAD



Silicon dose rates converted to H_2O; MSL-RAD and CRaTER adjusted for Earth's shadow @ ISS altitude.

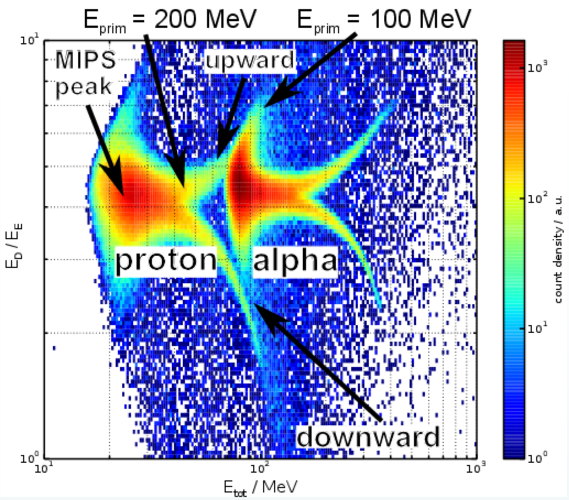
Angular Dependence of Charged Particles on Mars – R. Wimmer-Schweingruber

- Published in GRL Dec. 2015.
- Small deviations in A1*B/A2*B count ratio compared to isotropic case.
  - No dependence on local pressure changes or rover tilt angle.
- Within Curiosity's range of tilt angles ($0° \leq \theta \leq 15°$) while roving, determine $J \propto \cos^{\gamma}(\theta)$ with $\gamma = 1.18 \pm 0.07$.
- Isotropic field has $\gamma = 1.0$
- At sea level on Earth, $\gamma \approx 2.0$.

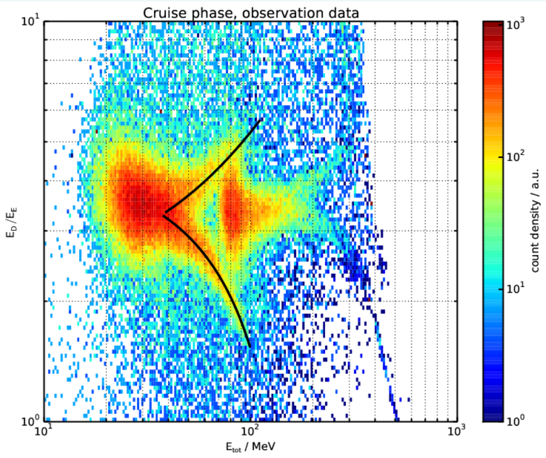


Albedo Protons (J. Appel)

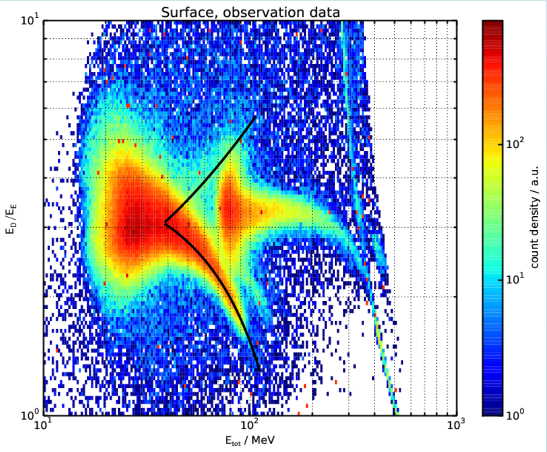
- Distinguish upward from downward particles from 100 - 200 MeV primary particle energy using D/E ΔE ratio.
- Cruise: Modeled spacecraft shielding environment with GEANT4, verified method.
- Surface: Modeled environment using Planetocosmics and Geant4, found good agreement between predicted and observed up to down ratios:
  - Simulation: 0.10 ± 0.01
  - Observation: 0.10 ± 0.02



Sim



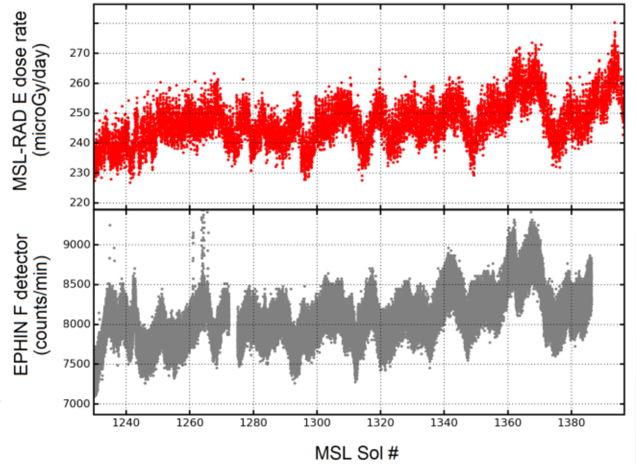
Cruise



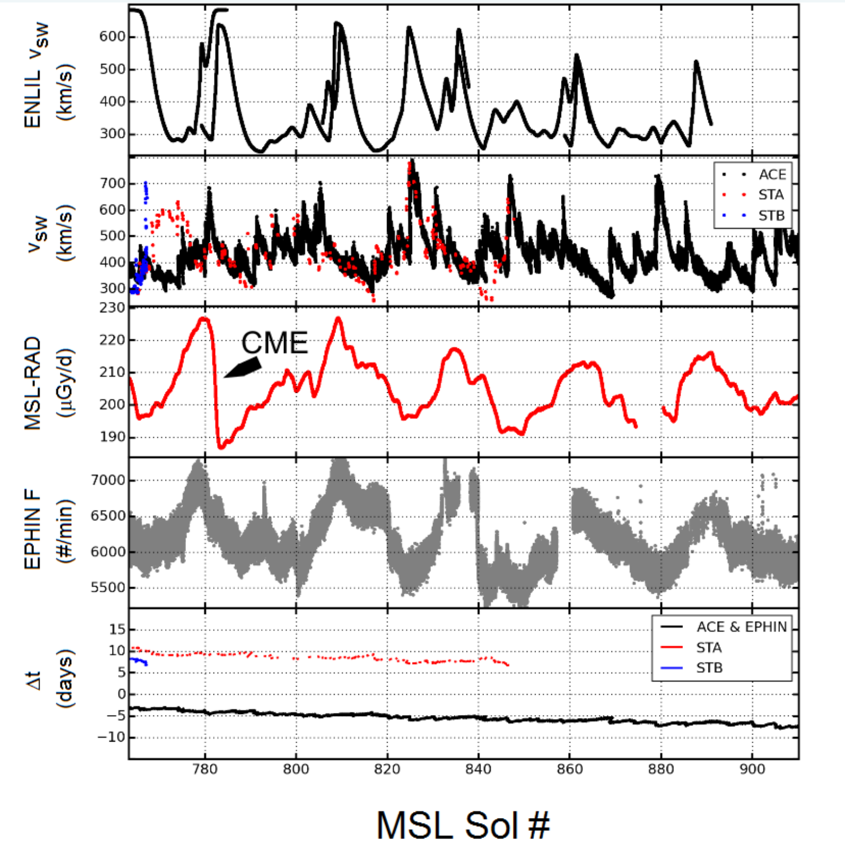
Surface

Co-rotating Interaction Regions (H. Lohf)

- Observations of interesting solar phenomena depend on the location of the observer.
- Idea: time-shift data from sensors around the heliosphere to account for of solar wind propagation time and solar rotation.
- $t_2 - t_1 = (\varphi_2 - \varphi_1)/\omega_{sun} + (r_2 - r_1)/v_{sw}$



Unshifted



Conclusions

- MSL-RAD science team remains active and generating publications.
- Instrument working flawlessly.
- Continuing efforts to improve configuration and extract new science.
  - Radon study in progress – easily seen in lab, on Mars have a very small signal (if any) on large background.
  - Neutron campaign still on the to-do list.
- Curiosity approved for second extended mission.