A Tale of Two RADs

And a CRaTER

Cary Zeitlin, NASA JSC SRAG

Science Teams

ISS-RAD: Cary Zeitlin, Martin Leitgab, Nic Stoffle, Kevin Beard, Ryan Rios

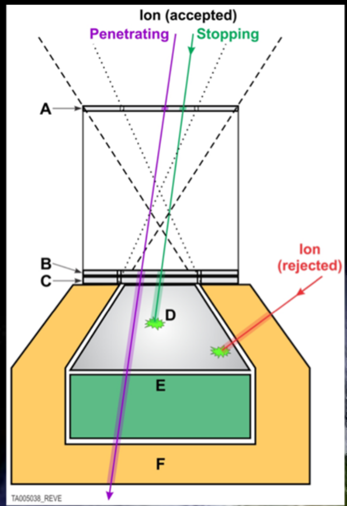
MSL-RAD: Don Hassler, Bent Ehresmann, Robert Wimmer-Schweingruber, Jingnan Guo

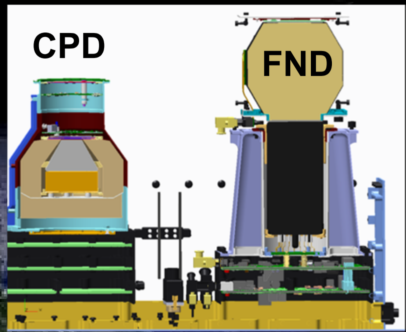
CRaTER: Harlan Spence, Nathan Schwadron, Jody Wilson, Mark Looper, Joe Mazur

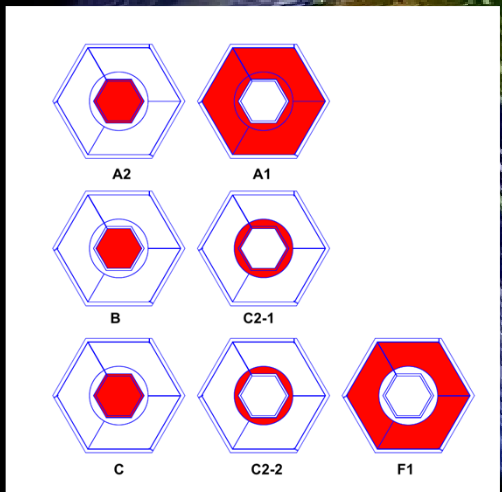
Overview

- ISS-RAD has been operating for 3.5 years as a survey instrument.
- MSL-RAD has been operating for 7 years in Gale Crater, shielded by ~22 to 23 g cm^{-2} of CO_2.
- ISS-RAD CPD is nearly identical to MSL-RAD & many measurements can be directly compared.
- Also use data from CRaTER aboard the Lunar Reconnaissance Orbiter.
  - Additional comparisons closer to unshielded or lightly-shielded deep-space conditions.

RSH ≈ CPD

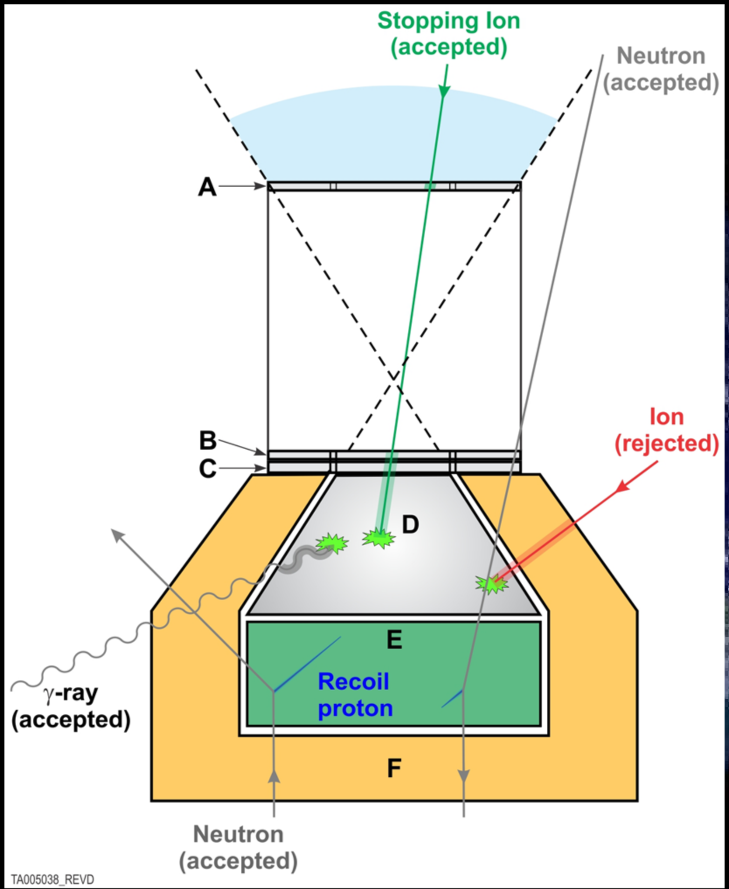






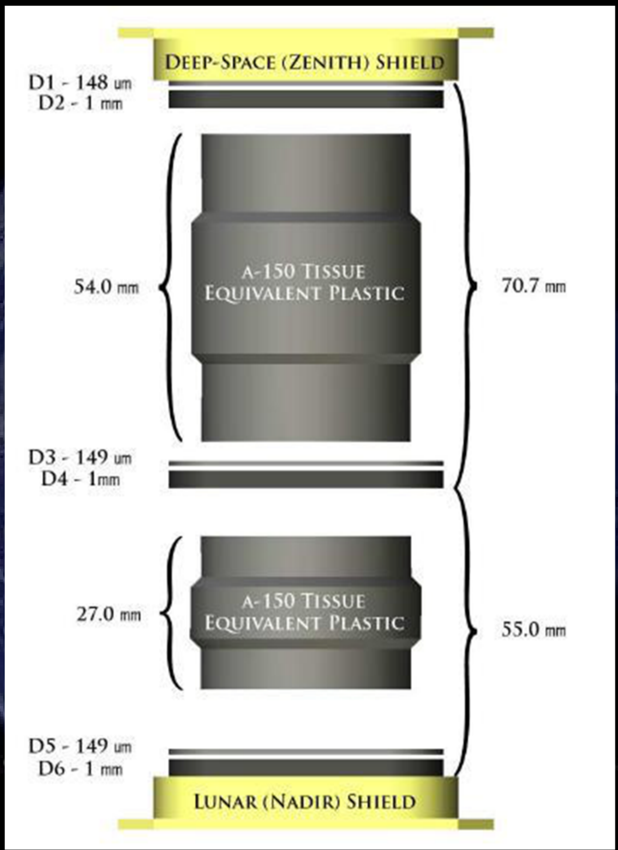
- **MSL-RAD has "RAD Sensor Head"**
- **ISS-RAD has "Charged Particle Detector"**
- **Charged particle coincidence triggers:**
  - **A1*B, A2*B (readout all hit detectors)**
- **Counters:**
  - **A2*B*C*D*E*F - penetrating particles**
  - **A1*B*C*D, A2*B*C*D - stopping particles**
- **Geometric factors:**
  - **A1*B = 0.72 cm^2 sr single-ended.**
  - **A2*B = 0.17 cm^2 sr single-ended.**
  - **Appropriate G depends on setting.**
- **D in ISS-RAD is BGO vs. CsI in MSL-RAD.**
- **E in ISS-RAD is EJ-260 green-emitting vs. BC-432 orange-emitting in MSL-RAD.**

Neutral Particles



- **Simplified picture of neutral particle detection in CPD: D detects γ-rays,E detects neutrons.**
  - **Particles incident from all directions.**
- **Reality: D also sensitive to neutrons, (esp. higher-energy) & E is a little sensitive to γ's.**
- **B, C, and F used to veto charged particles.**
  - **F in ISS-RAD is thicker (1.8 cm vs. 1.2 cm).**

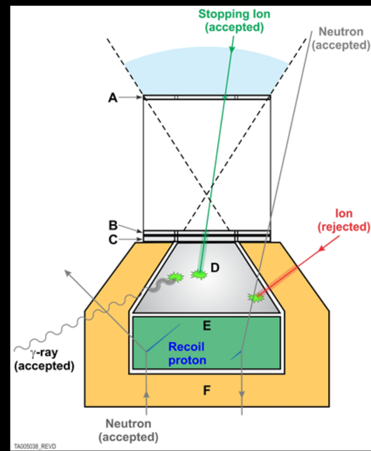
CRaTER on LRO



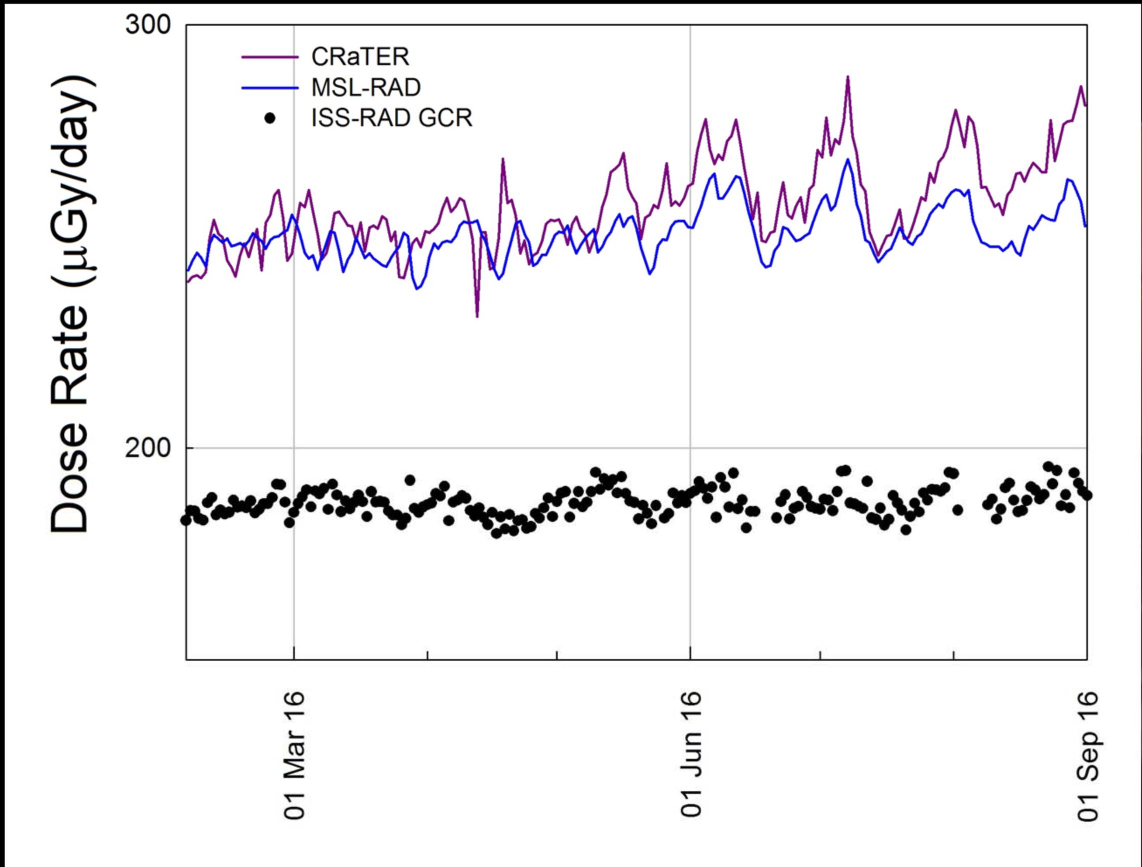
- **Elliptical polar orbit, 25 km periselene, 165 km aposelene.**
- **CRaTER telescope measures charged particles, allows tests of shielding by tissue-equivalent plastic (TEP).**
- **Deep space dose rates can be measured using D1 & D2.**
- **Last detector pair is shielded by 9 g cm^{-2}.**

Measurements to Compare

- **Dose rates - for ISS-RAD, strong variations with orbit. B and E detectors for "omnidirectional" measurements.**
- **Telescope dose rates using A*B coincidences.**
- **Count rates for stopping & penetrating charged particles.**
- **LET spectra & derived ICRP60 <Q>'s.**
- **Neutral particle ΔE spectra in D & E w/corresponding dose rates.**

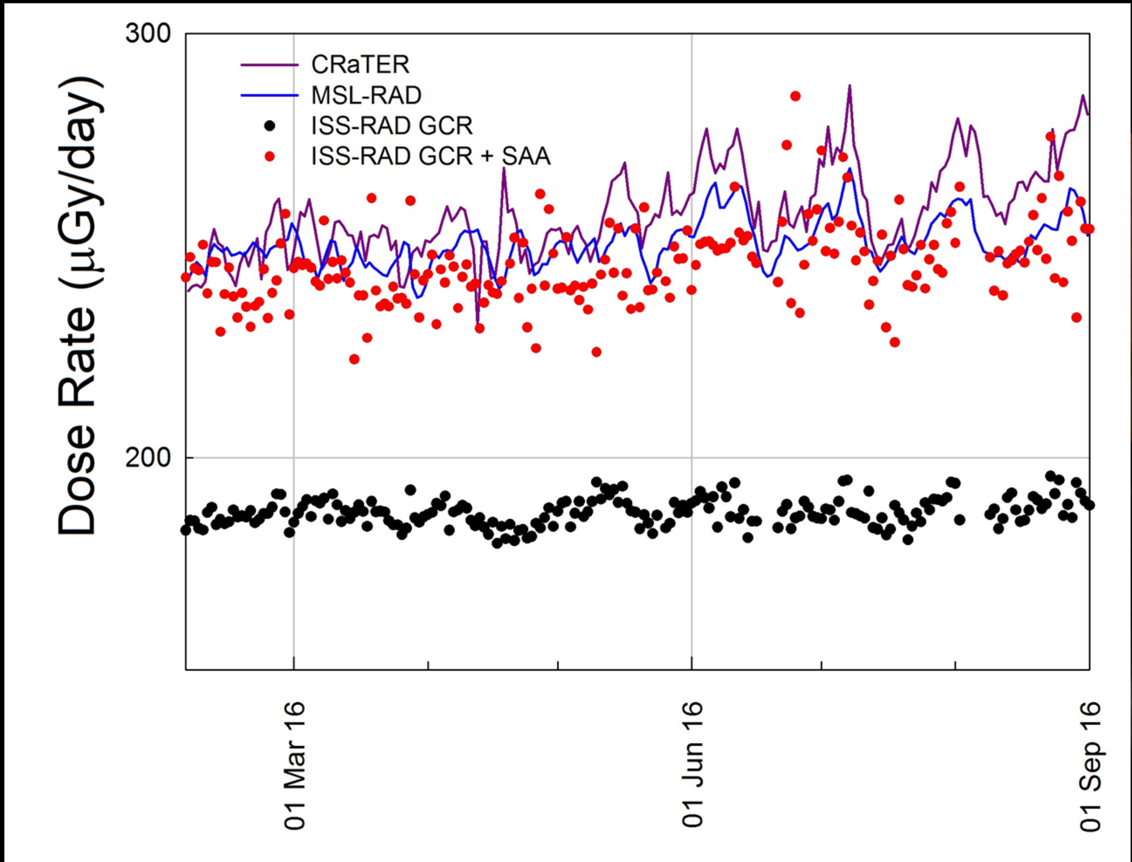


Average Dose Rates 2016



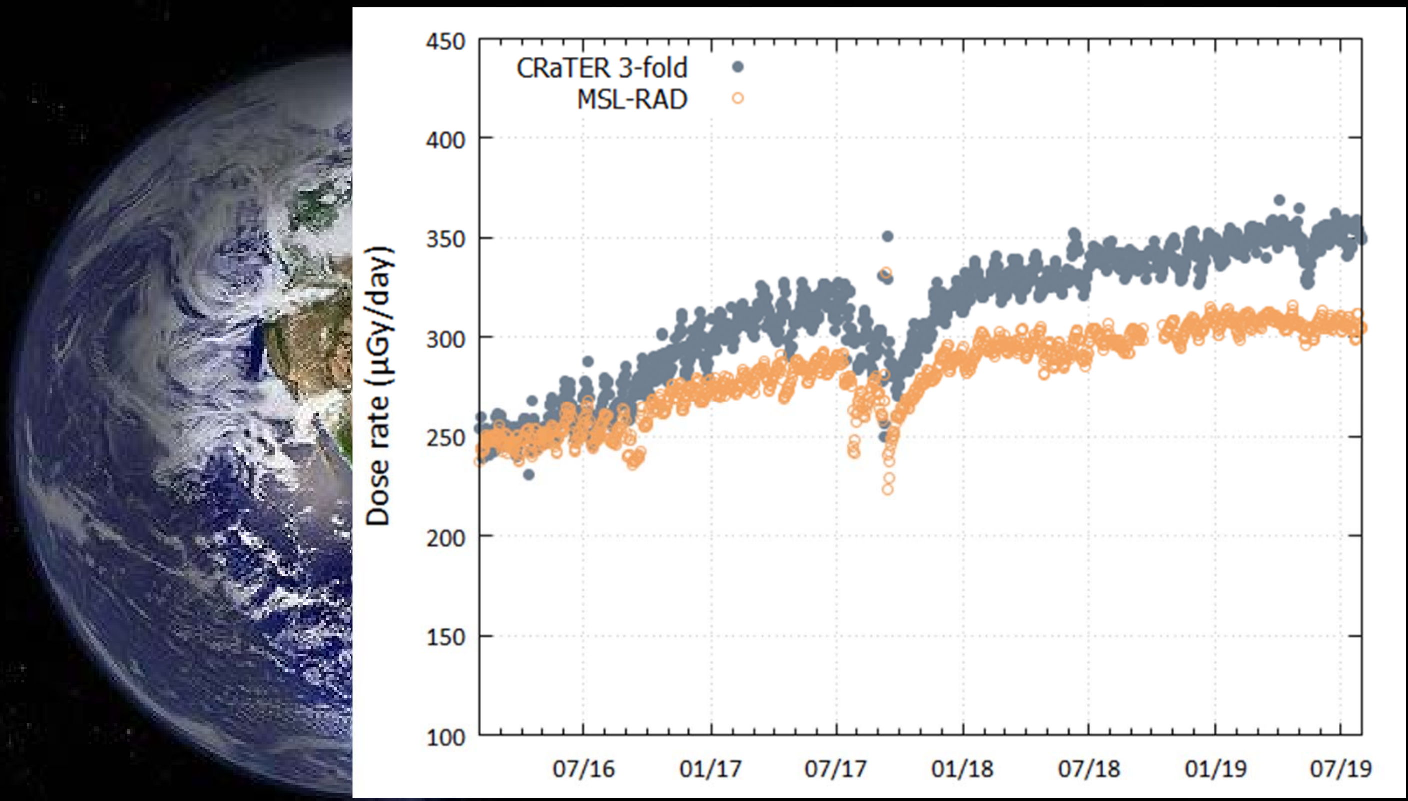
- **Daily-average GCR dose rates are suppressed in LEO.**
- **ISS-RAD in USLab in 2016.**
  - **ISS-RAD B data shown (Si converted to water).**
  - **MSL-RAD E data shown.**
  - **CRaTER also Si converted to water. Rates based on D2*D4*D6 coincidences - hits required all through stack, 30% “top of stack” correction applied. (Too large?)**

Average Dose Rates 2016

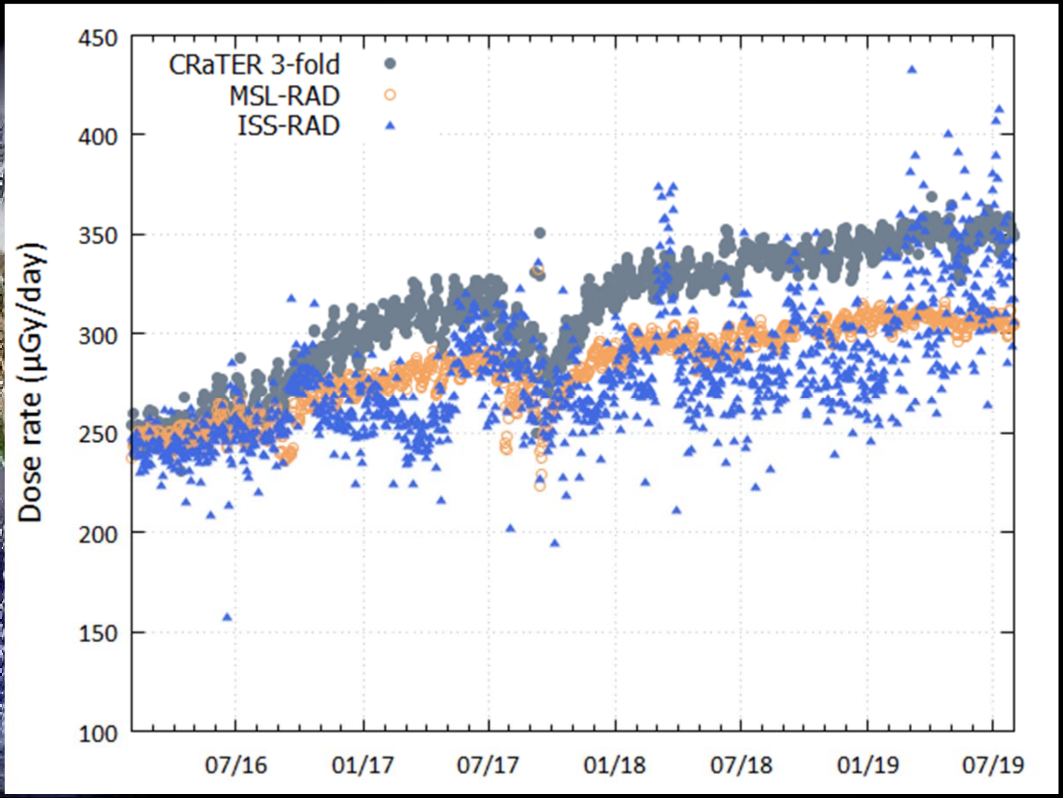


- **Total including SAA is line with deep space.**
  - **Significant day-to-day SAA variability mainly from orbit geometry & sometimes we miss a pass or two while data are being downlinked.**
- **Geometry is not apples-to-apples.**
  - **CRaTER dose rate is based on extrapolating a narrow view cone to 2π.**
  - **MSL-RAD ~ 2π since albedo dose is small.**
  - **At 410 km up, ISS-RAD has ~ 2.7π open.**
- **The near-equality seen in 2016 data seems to only hold for USLab.**

The Big Picture (So Far)

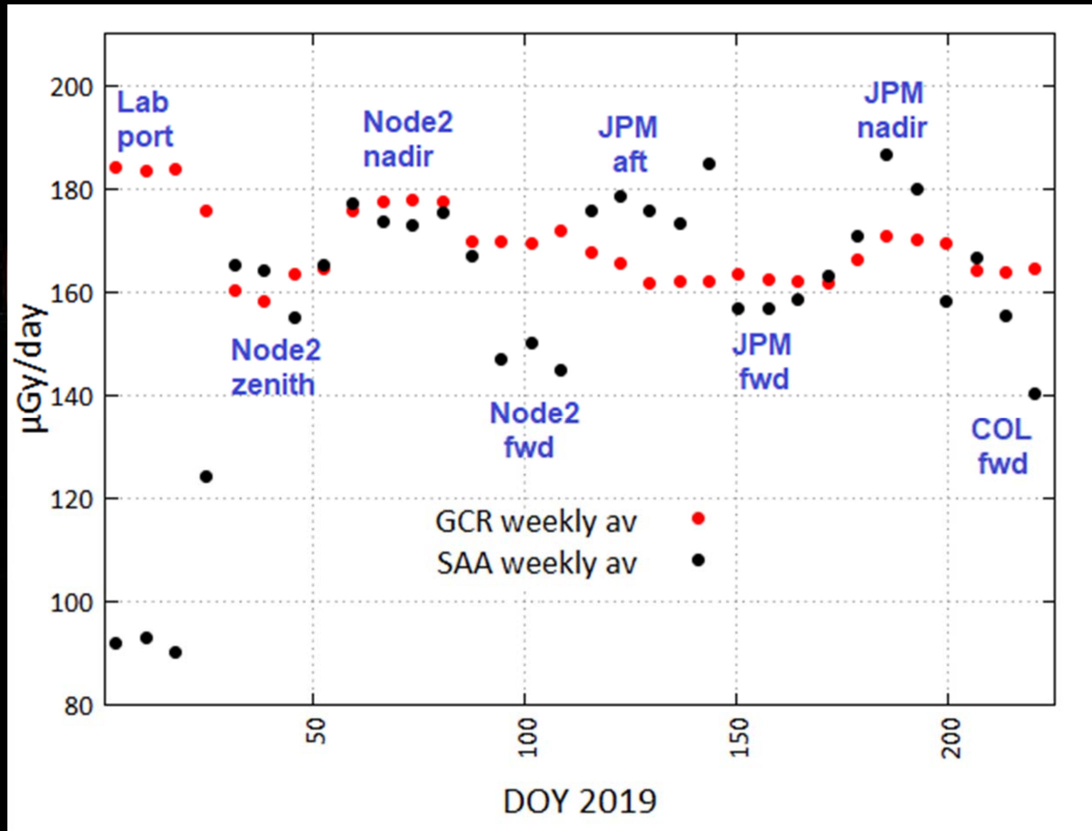


The Big Picture (So Far)



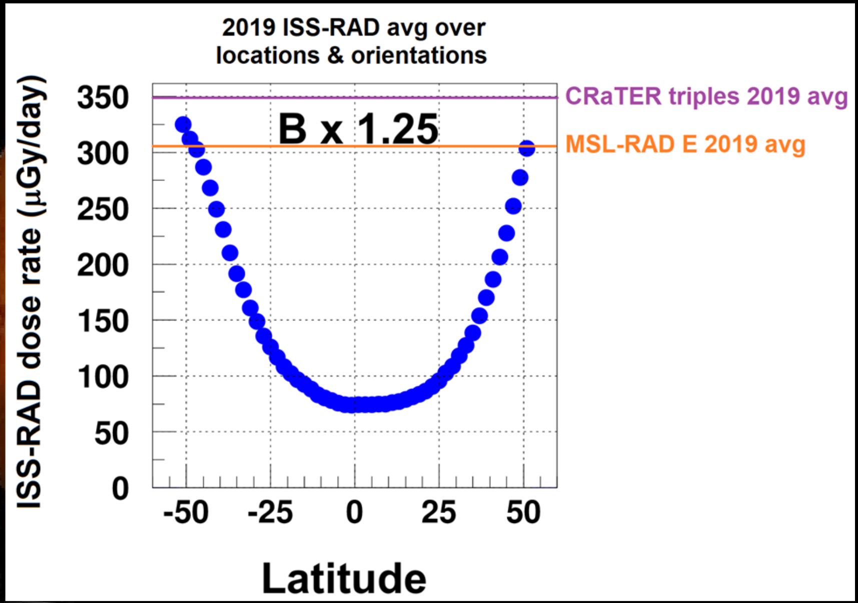
GCR/SAA Separation

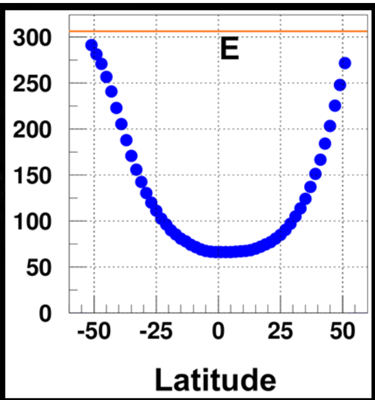
- **Variations in measured SAA doses drive the scatter seen in daily average dose rates.**
  - **Depends on location, orientation, & number of SAA passes on a given day.**
  - **Smooths out w/weekly average.**
- **2019 B-detector data shown, averaged per-week.**
  - **Note, sometimes relocates occur out of sync w/data dumps.**



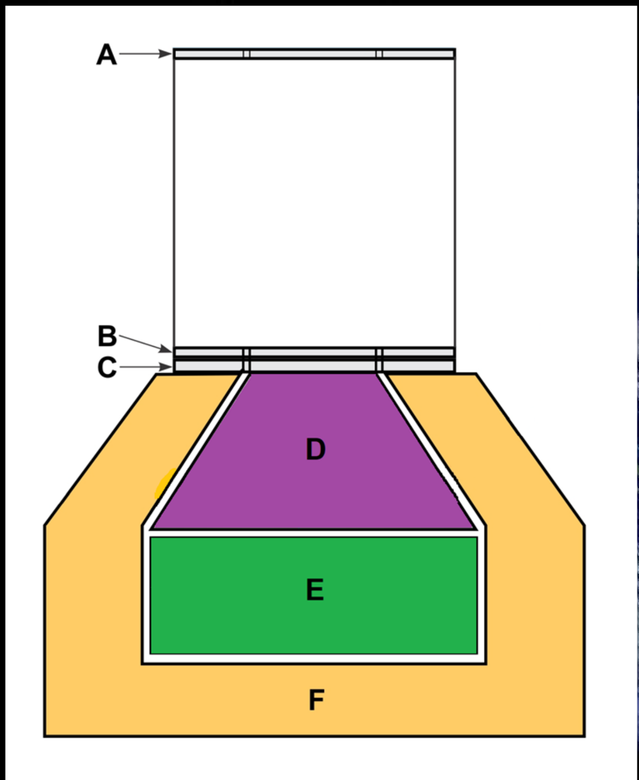
GCR-only Comparison

- **Top: B dose rate converted to water as a function of geocentric latitude with SAA data removed.**
- **At highest latitudes, rates are comparable to MSL-RAD E & CRaTER.**
  - **Geometry caveats apply.**
- **Similar plot using ISS-RAD E doesn't reach same peaks.**
  - **Quenching? MSL-RAD E shows little to none, but ISS-RAD material not identical.**





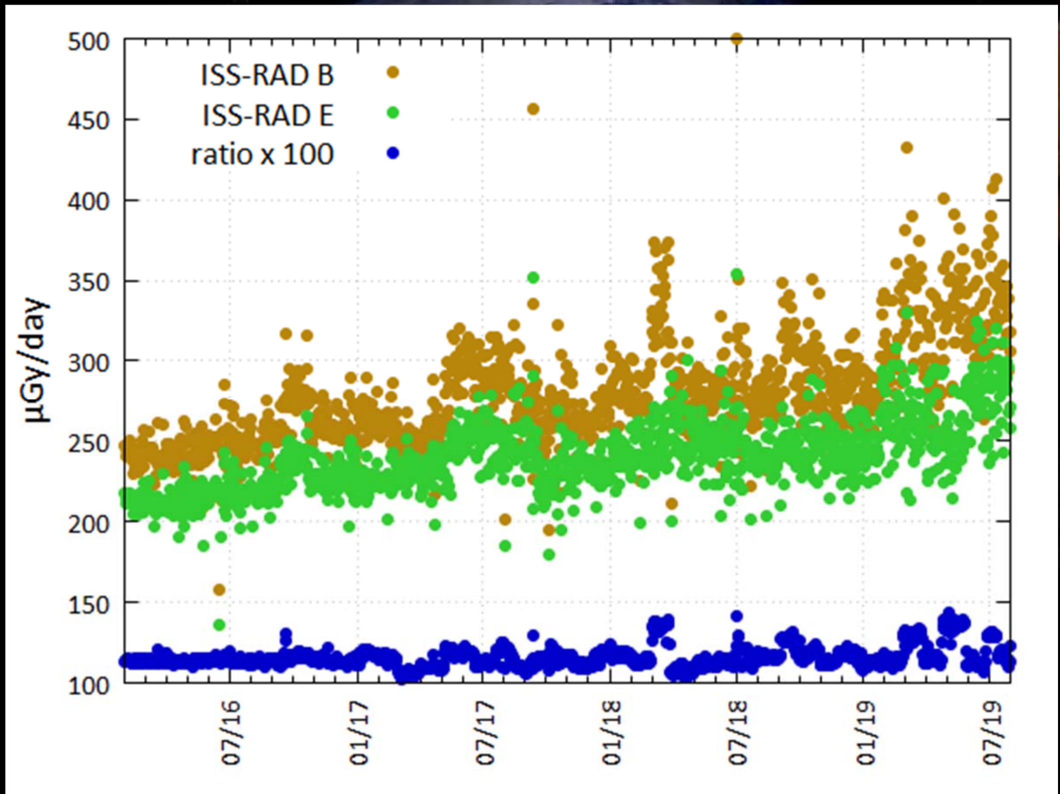
Dosimetry detector choice

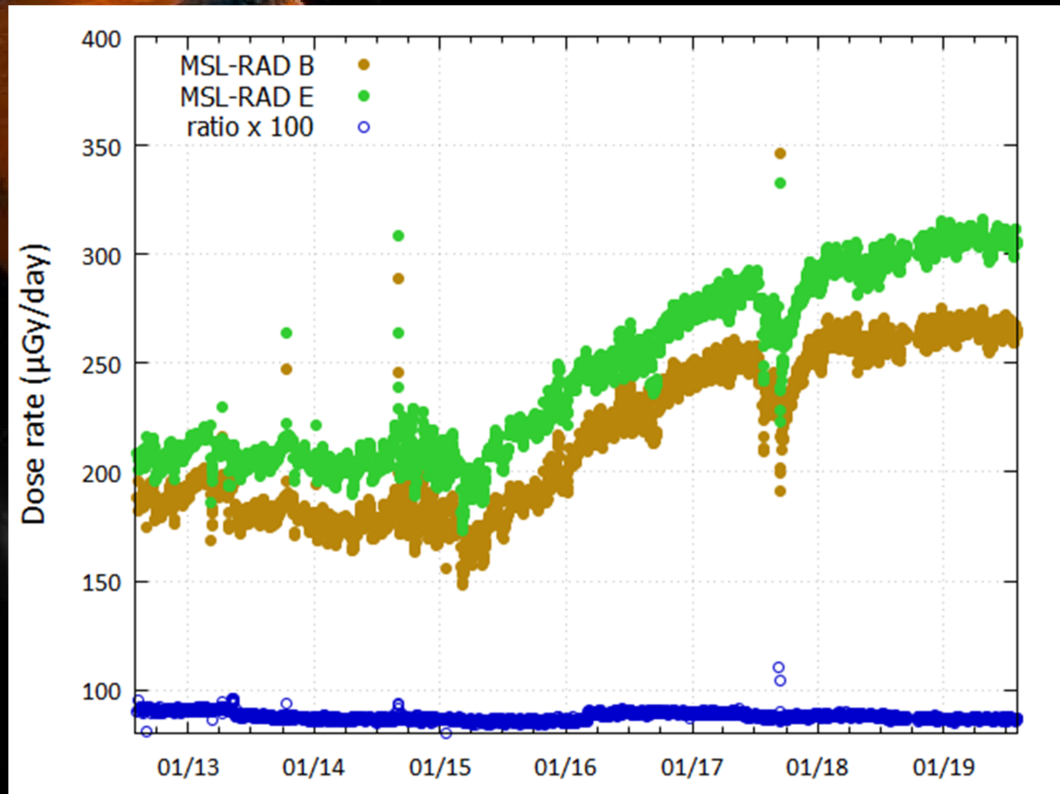


- We show B data for ISS-RAD (Si to water factor 1.25) and E data for MSL-RAD. Why?
- On MSL, RTG is ~1 m off to the side generating γ's, neutrons & secondary interaction products, including ~MeV e^-.
- Shielding of E by D & F stops these so E dose rates are ~ background free, vs. estimated ~ 67 μGy/day in B.
- On ISS-RAD, no RTG, but lots of lower-energy particles that don't reach E, and possible quenching of E response.

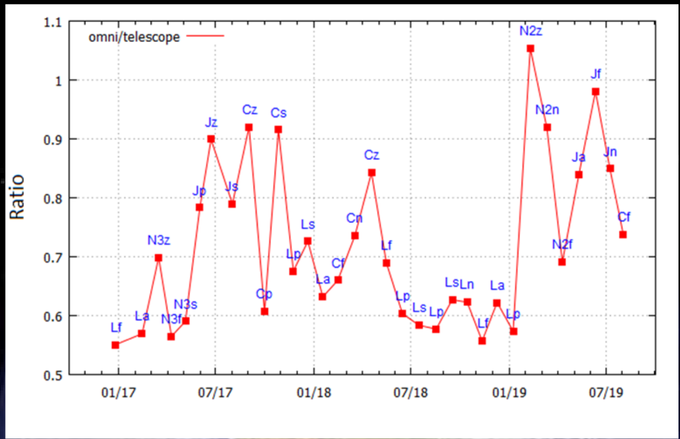
Environment Dependence?

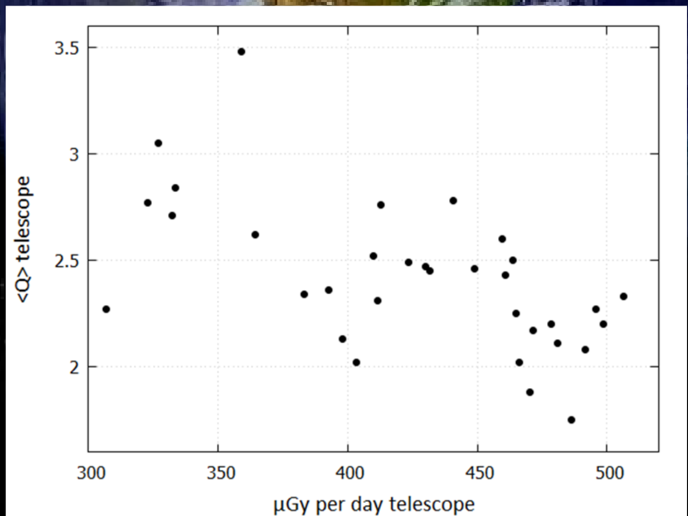
- **RAD B dose rates in silicon scaled by 1.25 in both cases.**
- **Ratios shown are 100*(scaled B dose)/(E dose).**





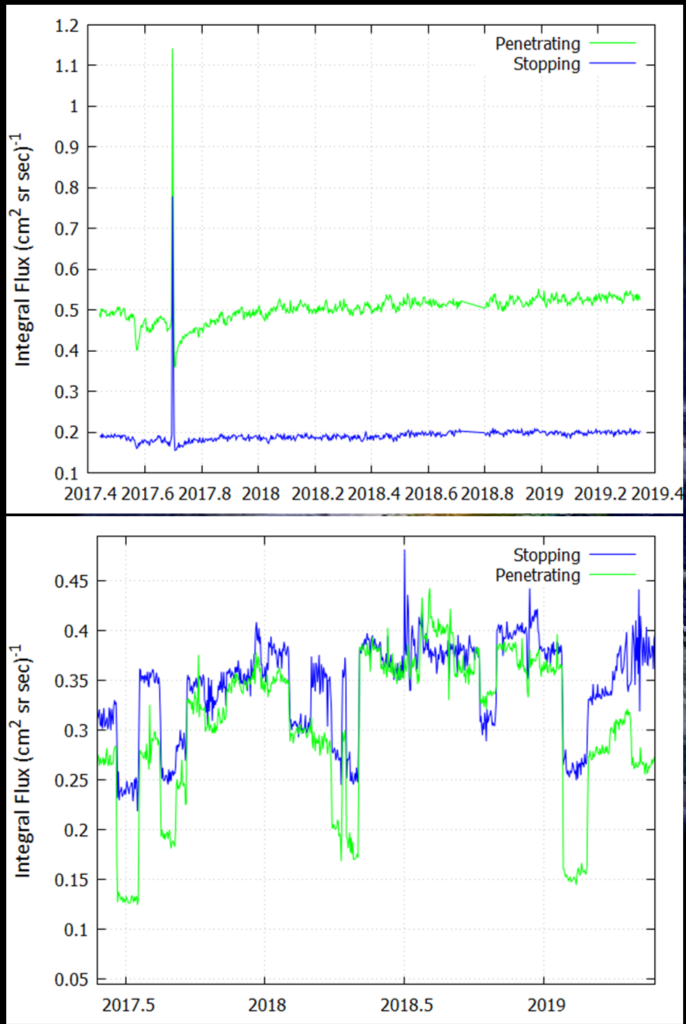
Telescope Dose Rates





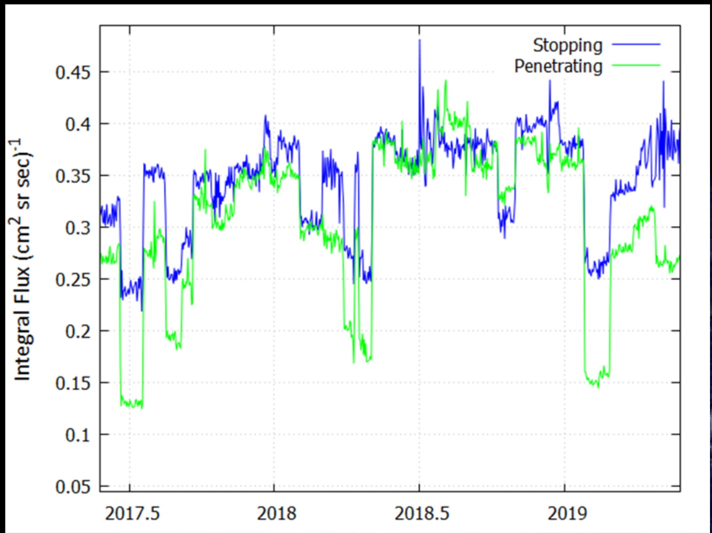
- Dose rates can also be calculated based on coincidence events in narrow FOV.
- Can extrapolate to arbitrary geometry, here 2.7π.
- In ISS data, telescope > omni.
- In MSL data, omni > telescope by factor of ~ 1.2. Why the difference?
- Ratio is hard to understand but zenith pointing gives peaks — why doesn't nadir-pointing?
- <Q> vs. telescope dose rate shows anti-correlation.

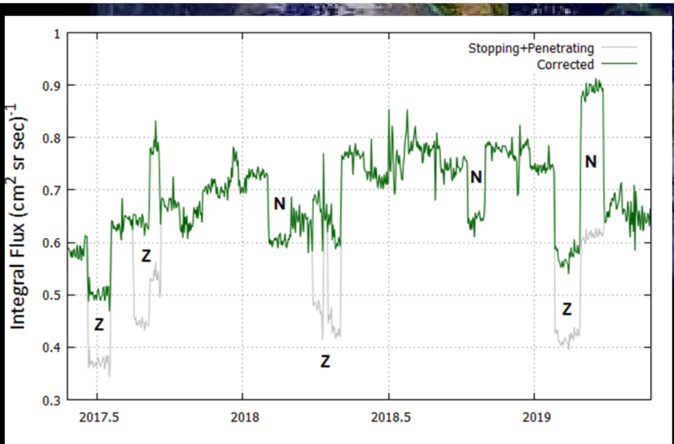
Stopping & Penetrating Fluxes



- **Stopping energies a little higher in ISS-RAD since BGO density > CsI density — e.g., protons up to 95 MeV stop in MSL-RAD D, up to 120 MeV in ISS-RAD.**
- **Normalize penetrating counts to double-ended G for ISS-RAD, everything else is single.**
  - **Zenith/nadir orientations obvious.**
- **Ratio of penetrating:stopping is completely different in ISS.**

“Corrected” Fluxes for ISS





- **Adjust normalization of periods in zenith or nadir to single-ended G for penetrating particles and sum w/stopping.**
- **MSL-RAD ~ constant sum ~ 0.7.**
- **Activity Log may need revision.**

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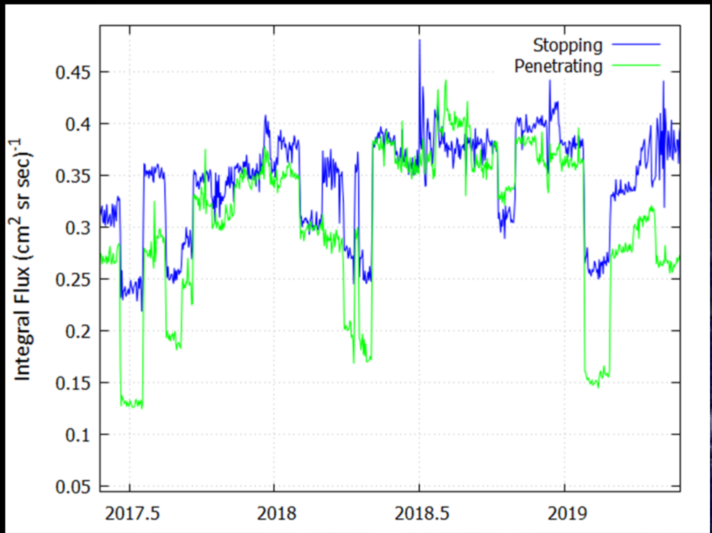

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- **Not really pointed zenith for the full month around 7/17.**

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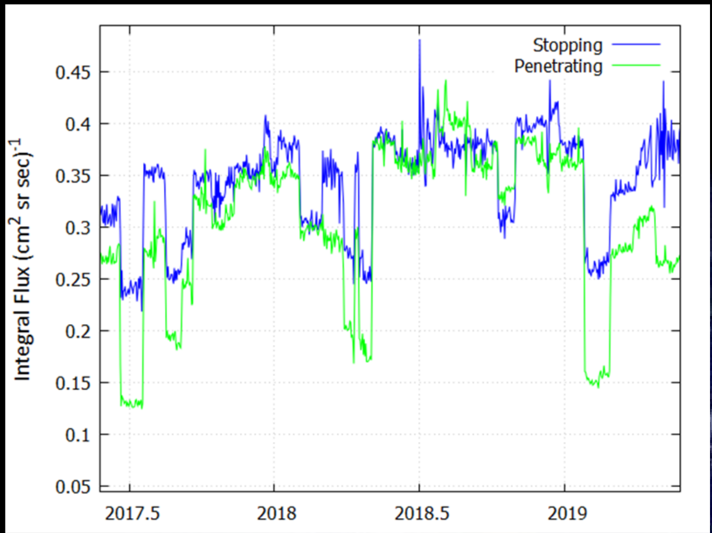
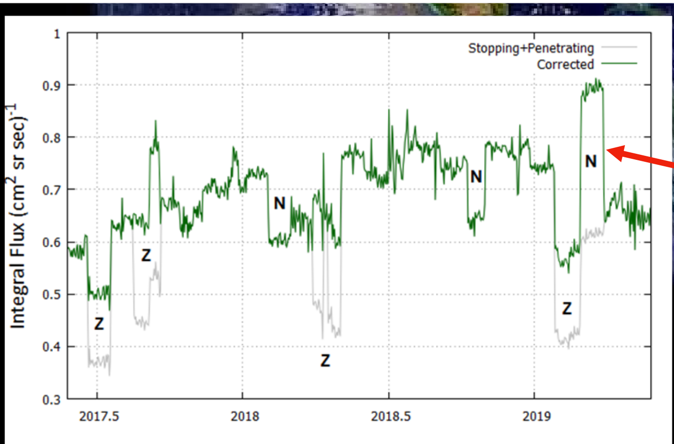
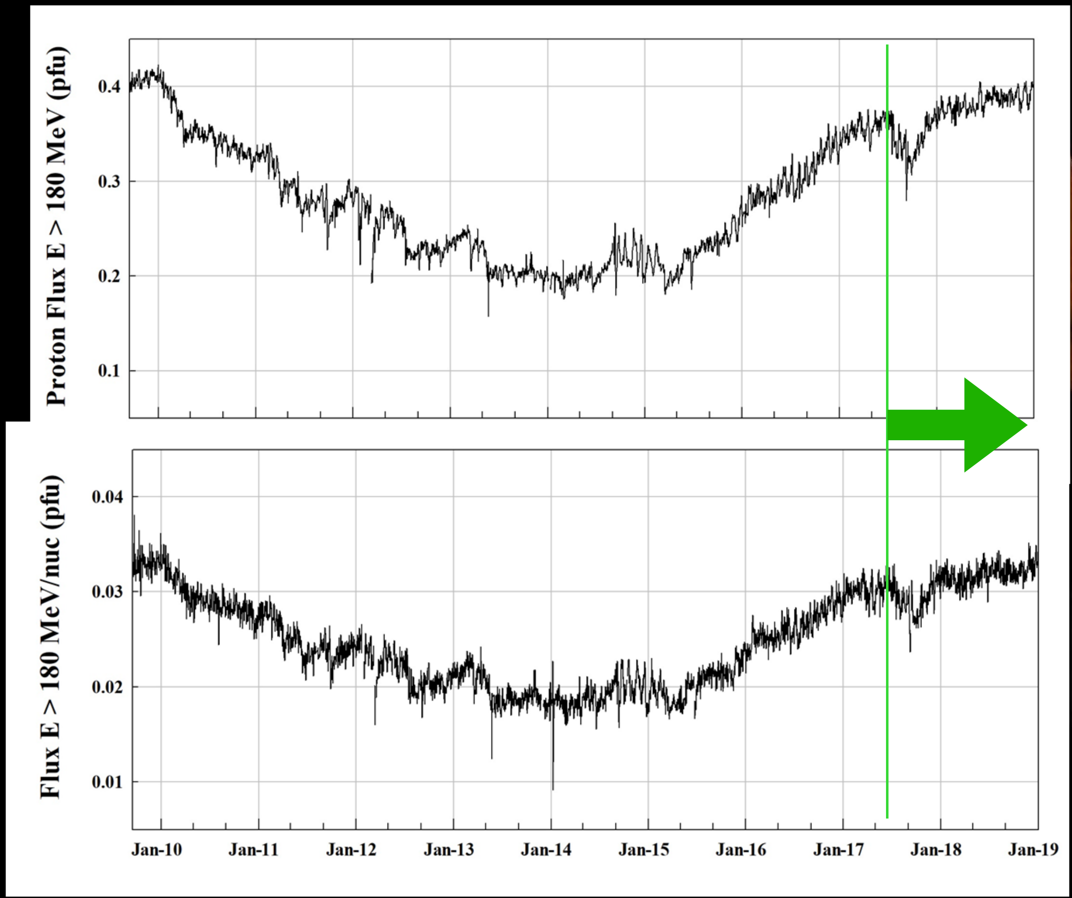




- **Adjust normalization of periods in zenith or nadir to single-ended G for penetrating particles and sum w/stopping.**
- **MSL-RAD ~ constant sum ~ 0.7.**
- **Activity Log may need revision.**
- **Not really pointed zenith for the full month around 7/17.**
- **Apparently not pointed nadir in early 2019.**

Integral Flux Compared to CRaTER



- RAD penetrating particle integral flux is ~ 0.5 pfu since mid-2017, slowly rising.
  - Threshold proton energy to reach RAD & penetrate is ≈ 220 MeV.
  - Just A2*B*C*D*E*F counts, includes events that would fail reasonable selection criteria.
- CRaTER F_{180} (integral proton flux E > 180 MeV) is ~ 0.4 pfu & He F_{180} ~ 0.03 pfu with tight selection cuts.
  - Sum reasonably close to MSL-RAD.
  - Is less shielding playing a role as well?

Sidebar — F_{180}

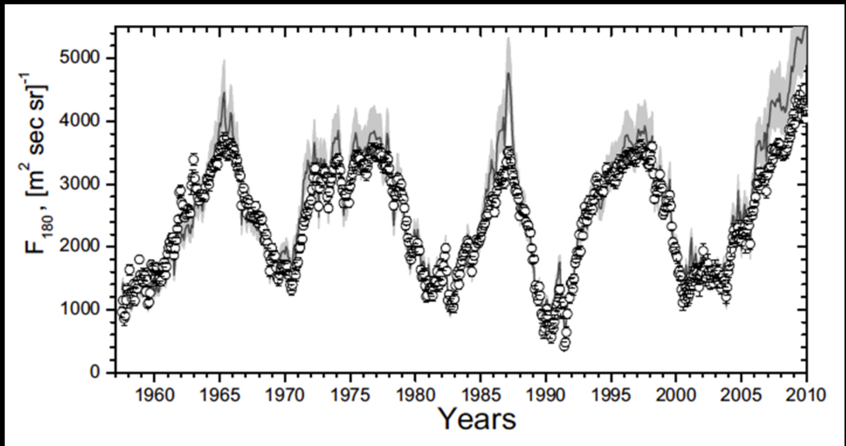
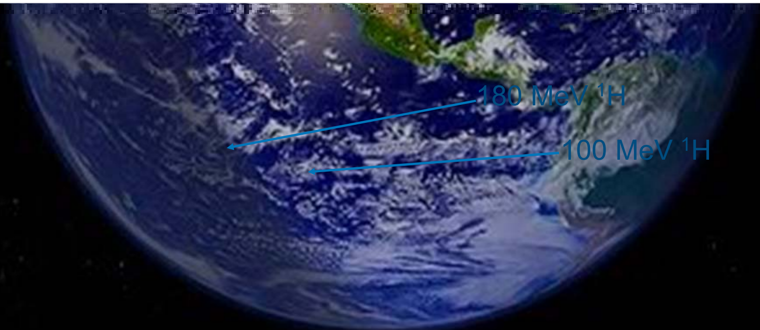
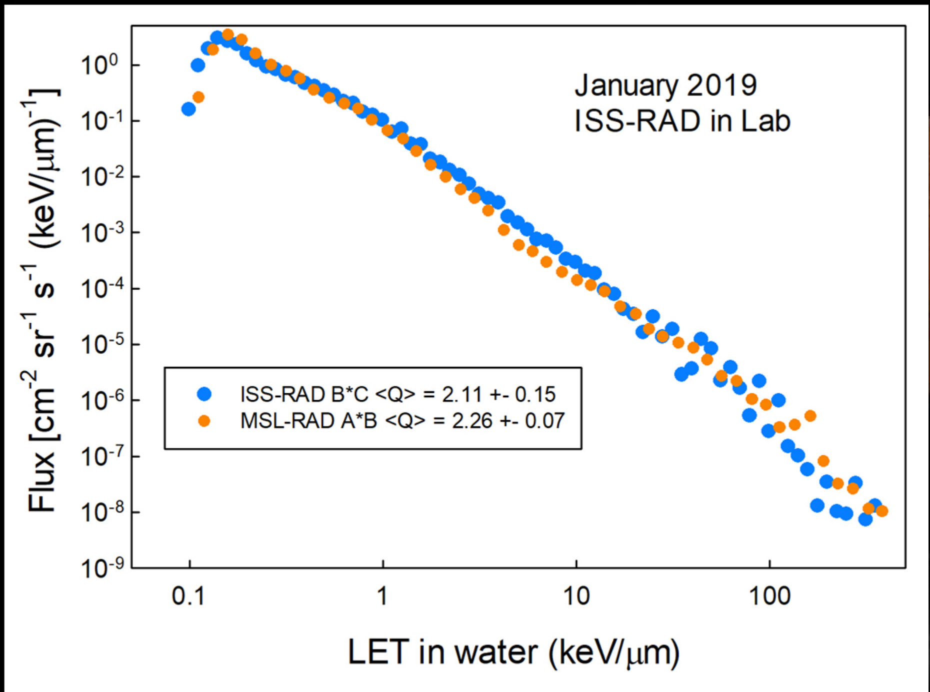


Figure 2: Time profile of the cosmic ray flux (> 180 MeV/nuc) F_{180} as measured at the Lebedev Physical Institute balloons (open dots with error bars) and computed from NM-data (solid curve with grey shading denoting 1σ uncertainty).



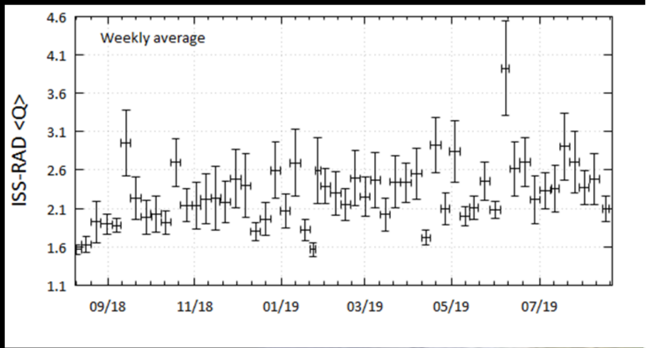
- **Reported in balloon data used by Usoskin et al. in modeling of NM data.**
- **180 MeV is a good cutoff energy to use in CRaTER data to insure proton sample is clean.**
- **Note 2010 balloon data show F_{180} ~ 0.41 pfu, similar to CRaTER results.**

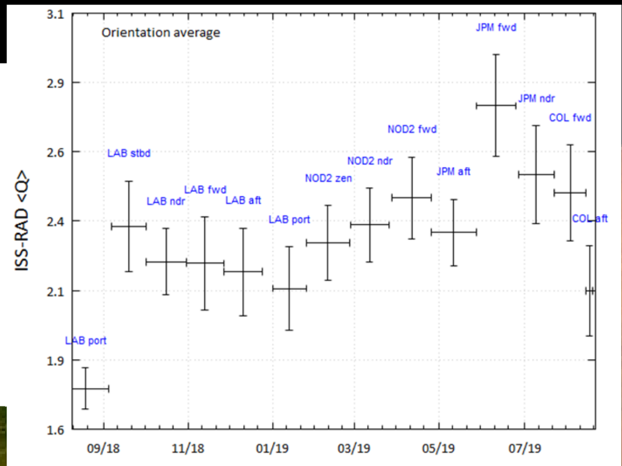
LET Spectra

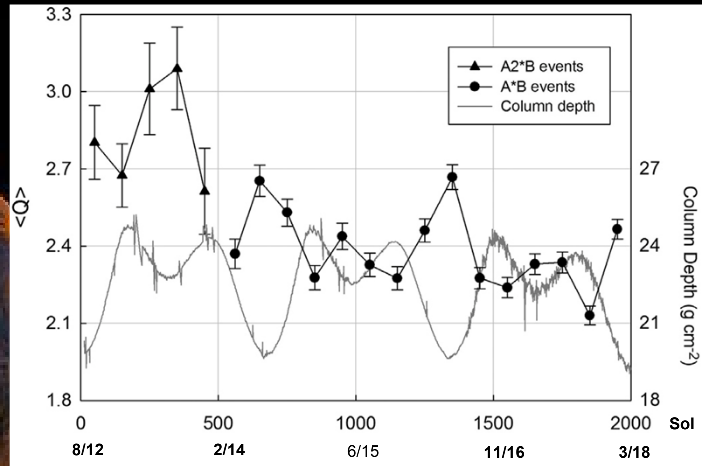


- **For ISS-RAD, use heavily-prescaled event sample in ground analysis.**
- **No separation of GCR/SAA in this plot due to lack of timestamps.**
  - **Can achieve separation with FND prescale factor as proxy.**
  - **Next version of FSW will supply timestamps.**
  - **Backed out the auto-prescale that was throttling the number of SAA events telemetered.**
- **Spectra & <Q> values similar.**

<Q> Results



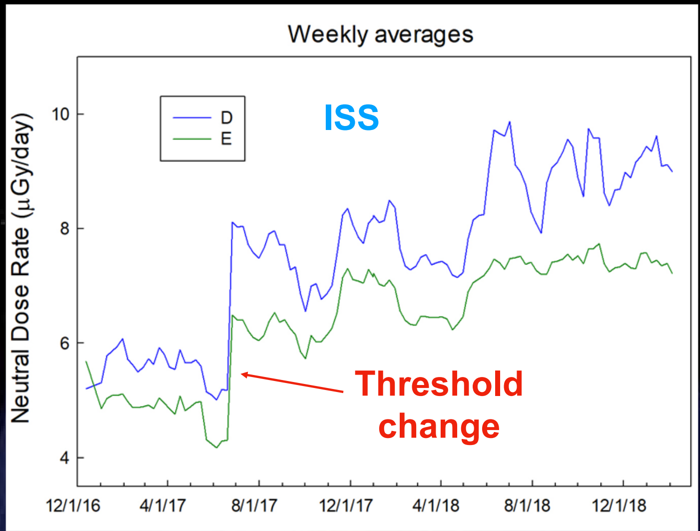


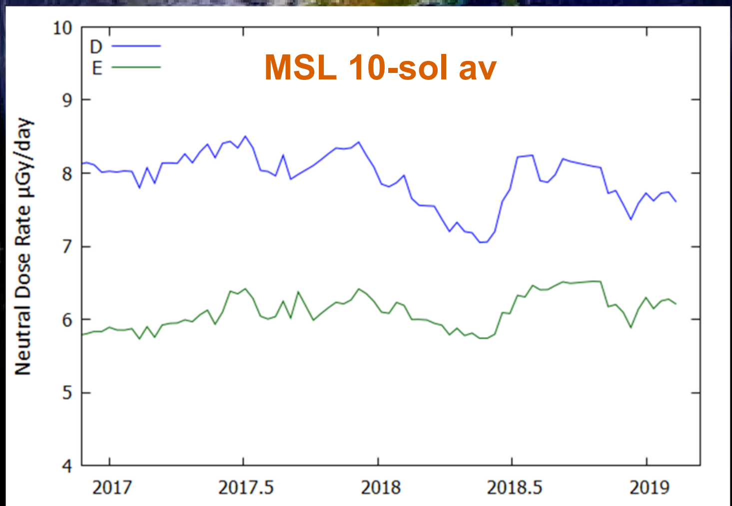


- **ISS-RAD data are noisy with 1-week intervals, smooth when averaged over full time in a given orientation.**
- **Noise is driven by fluctuations in counts of high-LET ions.**
- **Little variation over the past year despite relocates.**
- **Overall, since 1/17, <Q> = 2.25 ± 0.15.**

- **MSL-RAD data just published.**
- **1 sol = 1.027 Earth days & sol 1 was 8/7/2012.**
- **Column depth of atmosphere plays a role, but declining <Q>'s seen ~ independent of pressure.**
- **<Q> for surface mission: 2.37 ± 0.26.**

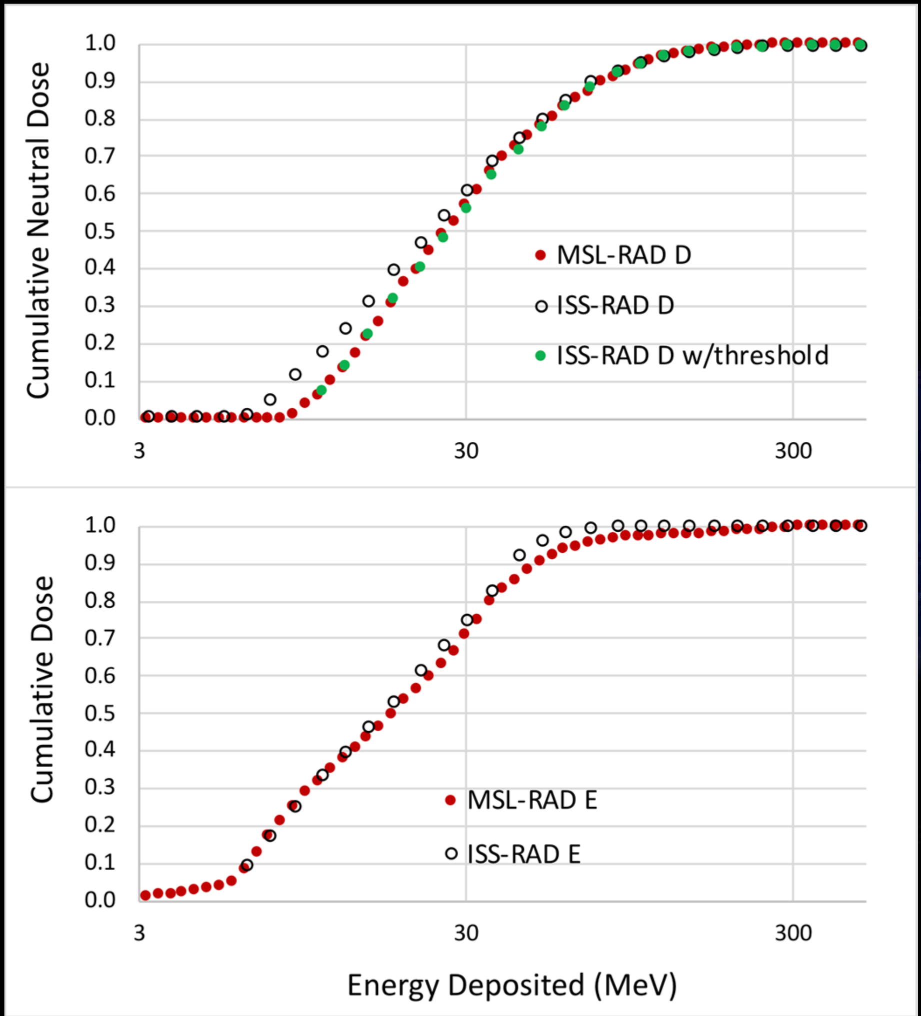
Neutral Particle Doses





- Dose rates calculated from onboard neutral-particle histograms from both RADs.
- Lower thresholds in ISS-RAD, esp. for D.
- ISS-RAD D rate: 5 to 10 μGy/day.
- MSL-RAD D rate: 7 to 8 μGy/day.
- ISS-RAD E rate: 4 to 7 μGy/day.
- MSL-RAD E rate: 5 to 7 μGy/day.
- E dose mostly neutrons, D a mix.

Neutral Particle Cumulative Doses



- ISS-RAD D has lower threshold than MSL-RAD D (kept high to suppress counts from RTG γ's).
- Artificially raise ISS-RAD D threshold in ground analysis, resulting CDF ~ MSL-RAD.
- Modeling suggests ~ 1/2 the D dose & ~ 1/4 of the E dose are due to γ's.

Neutron/γ Inversion

MSL-RAD Power-Law Results

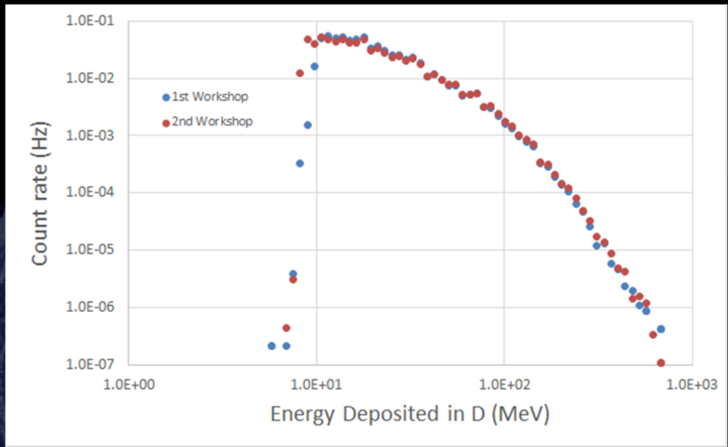
Power-law inversion results	Gamma spectra		Neutron spectra	
	I_γ /(cm² s MeV)	$-S_\gamma$	I_N /(cm² s MeV)	$-S_N$
Sol 1-194 (Kohler et al 2014)	1.6±0.6	1.43±0.1	0.08±0.03	0.72±0.07
Sol 1164-1224 (Guo et al 2017)	0.39±0.07	1.42±0.05	0.05±0.01	0.86±0.03
Sol 1980-2098 (Current study)	0.26±0.04	1.34±0.04	0.06±0.01	0.88±0.05

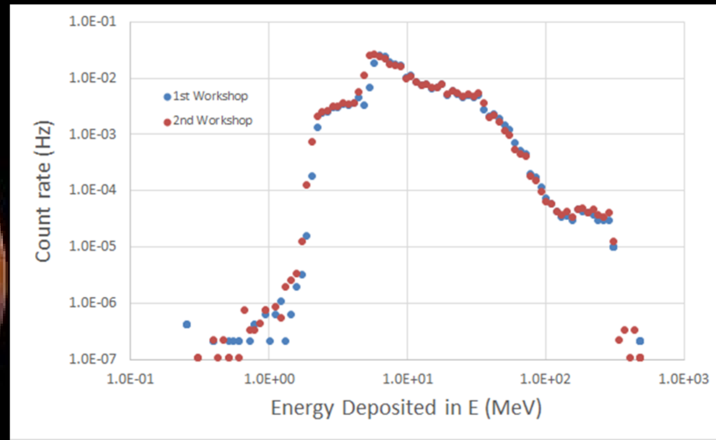
Work by Jan Koehler & Jingnan Guo

Normalization issues in Jan's work caused by a scaling problem discovered after publication.

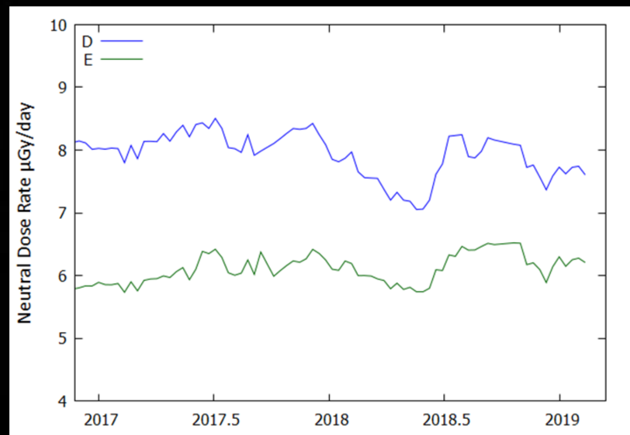
- **CBE for MSL-RAD n^0 dose equivalent from inversion 24 ± 4 μSv/day *for the measured range*.**
  - **Total including energies below threshold is larger.**
- **Problems w/software implementation have prevented us from unfolding the CPD neutral spectra as has been done with MSL-RAD.**
- **Current plan is incorporate "turnkey" inversion into MSL-RAD data pipeline. Same code used for ISS, hope to get it fixed in ISS-RAD application.**

MSL-RAD Workshop n^0 Results

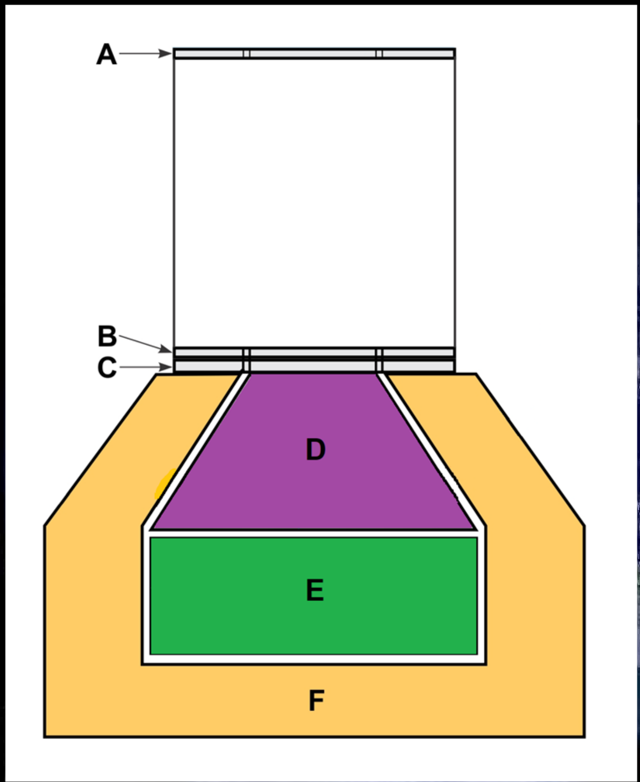




Power-law inversion results	Dose rate uGy/day			Dose equivalent rate uSv/day		
	Mean total measured	**Neutron (7-740MeV)**	**Neutron (1-1000MeV)**	**Mean total measured**	**Neutron (7-740MeV)**	**Neutron (1-1000MeV)**
Sol 1-194 (Kohler et al 2014)	214 ± 7.8	14 ± 4	19.7		61±15	83
Sol 1164-1224 (Guo et al 2017)	**233 ± 12**	**5.1 ± 1.0**	6.4	**610±45**	**23.6±4.1**	29.7
Sol 1980-2098 (Current study)	**301 ± 8.4**	**5.5 ± 1.0**	6.6		**26.1±4.1**	31.4



Caveats Re: Neutral Results



- The detection method limits the energy range we measure.
- Require scintillation light > noise threshold of ~ 2 MeVee. High since p-i-n diodes have no gain.
- In n^0+H collision, on average ~ half the kinetic energy is transferred so efficiency is small for energies below ~ 4 MeV.
- On MSL, have to set thresholds higher (~ 5 MeV in E, ~ 8 MeV in D) due to RTG.
- At high energies, recoil protons or other products are likely to escape D or E & fire the veto.
- Inversion & other interpretation of data are heavily model-dependent, but simple dose rates may be reasonably accurate.

Conclusions

- **The ISS radiation environment is comparatively dynamic, but on average is much like Mars and not too different from the Moon.**
- **Orbit-averaged ISS charged-particle environment is softer due to the combination of SAA and, for GCRs, energy lost traversing the geomagnetic field & in bulk shielding.**
- **Many similarities:**
  - **Dose rates, <Q>'s, integral charged particle fluxes (when stopping and penetrating are summed), neutral particle dose rates, neutral particle dose CDF's.**
- **Hope to have neutron/γ inversion code working soon for ISS data, but present analysis suggests results will not be very different than Mars.**


THANK YOU FOR YOUR ATTENTION!
THANKS TO THE ORGANIZERS FOR A **GREAT** MEETING