Update on radiations measurements on the surface of Mars conducted with MSL/RAD

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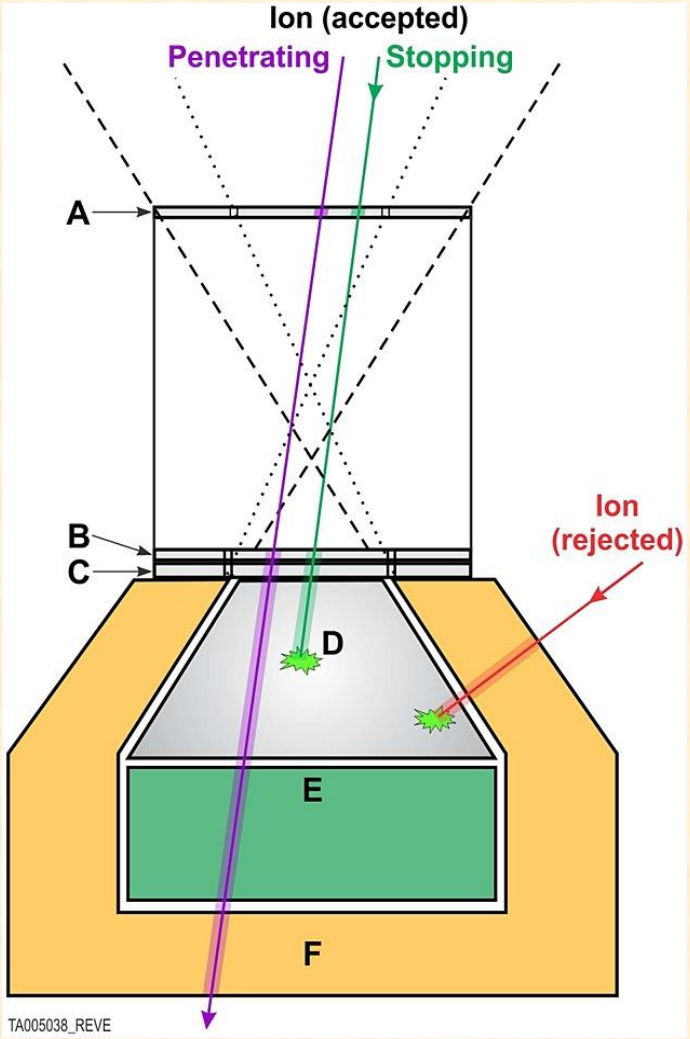
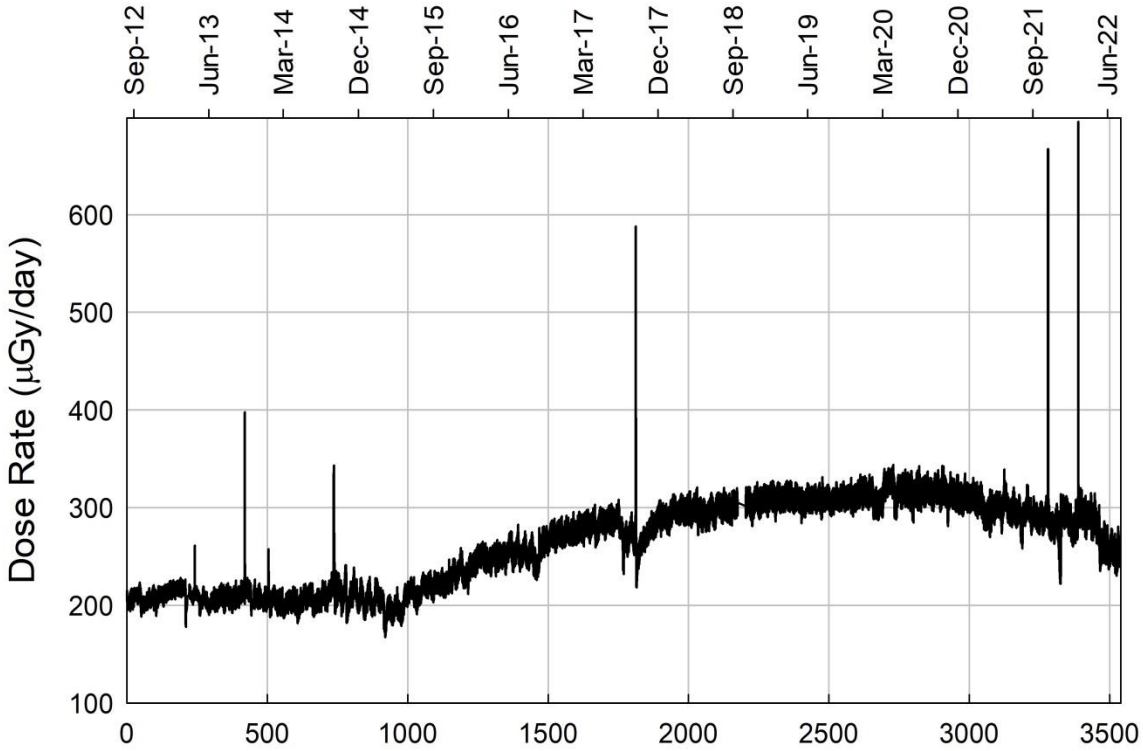
The RAD Instrument (Overview)

- ***RAD*** is a charged & neutral particle analyzer operating on the surface of ***Mars since 2012***
- RAD detects ***absorbed dose*** in ***B*** (Si) & ***E*** (tissue-equivalent plastic) detectors
- ***LET*** in Si is measured in ***B*** in coincidence with ***A*** (also Si)
- ***Neutral particles*** are detected in scintillators ***D*** (CsI) & ***E***
- ***Charged particle*** fluxes & spectra are determined in ***A – E***



RAD Dose Rate Measurements during the MSL mission

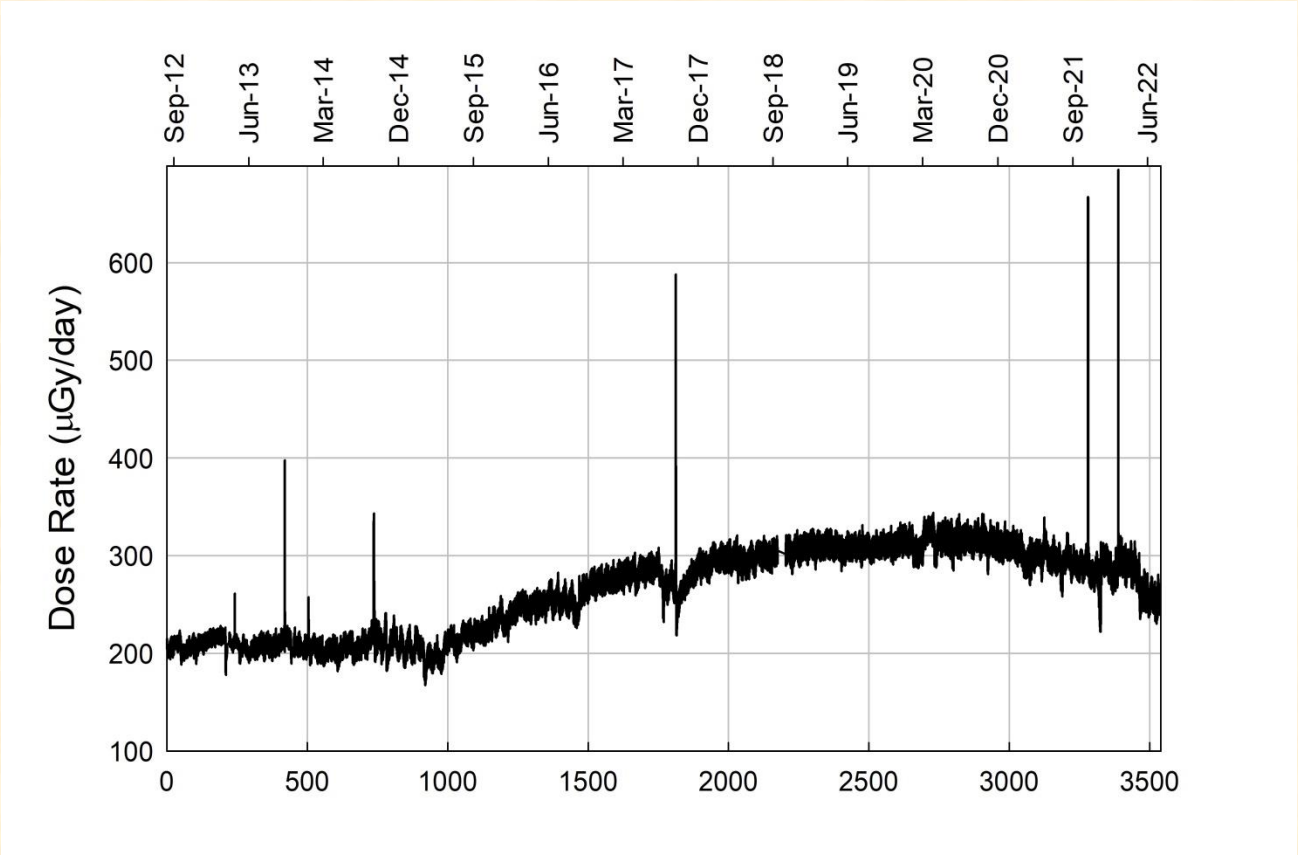
- Surface radiation nominally dominated by ***GCRs***
- Atmospheric shielding above RAD ***~20 – 23 g/cm^2***



- RAD absorbed dose rates (in E) have ranged from ***~210 μGy/day*** in 2012 (near weak solar max) to ***315 μGy/day*** in Mar / Apr 20 (deep solar min)

RAD Dose Rate Measurements – Evolution throughout the Solar Cycle

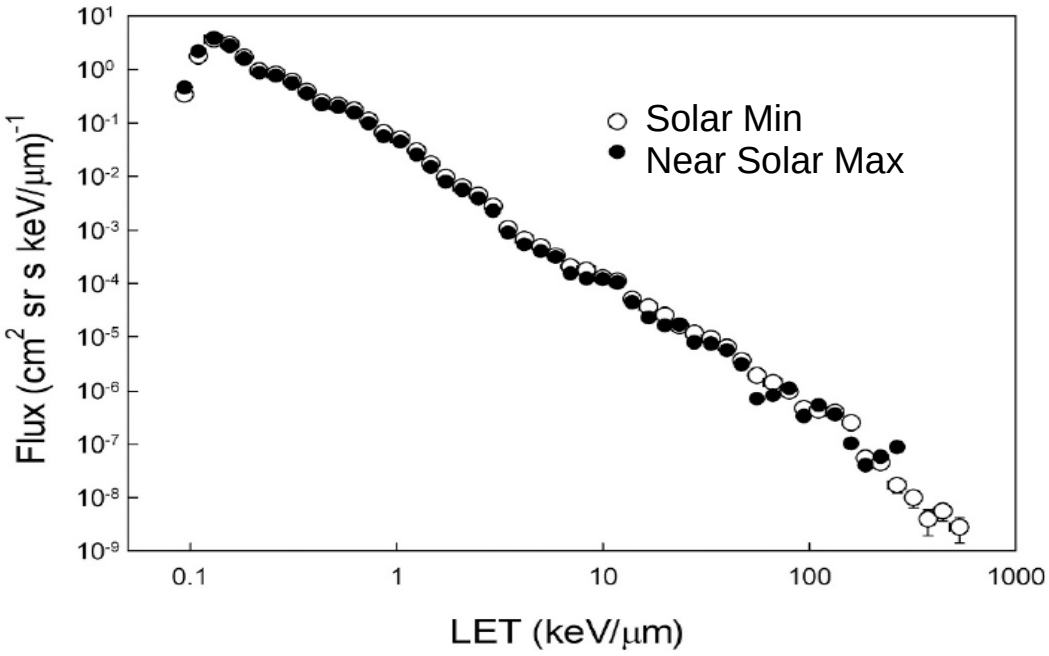
- What does a 50% increase in absorbed dose mean for Mars exploration?
- Increase from near (weak) solar max to deep solar min
- RAD can give indications by providing dose equivalent



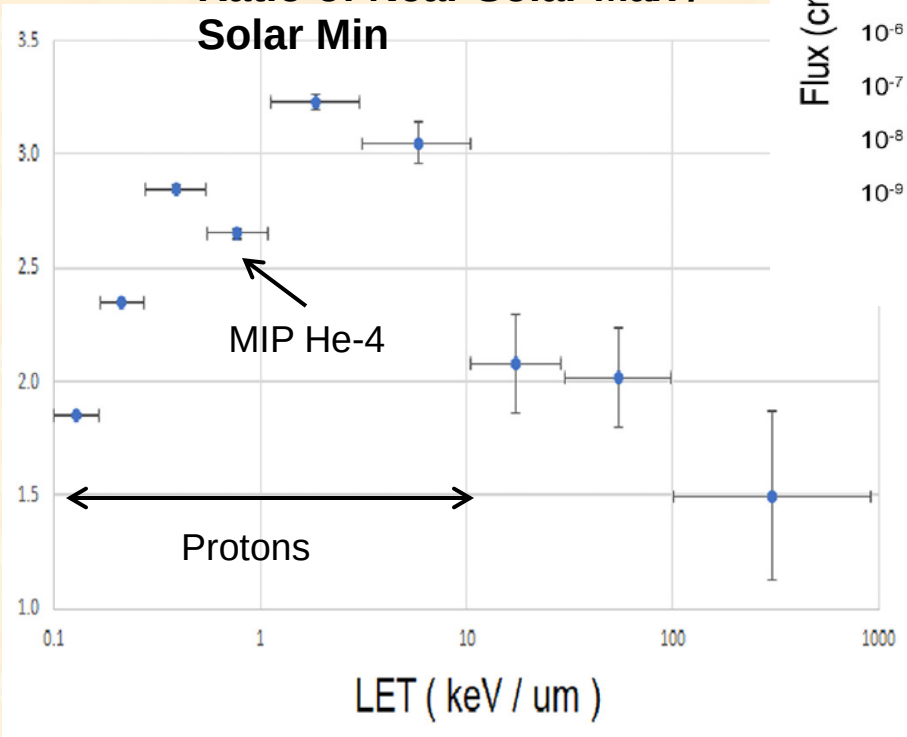
- Dose equivalent: Absorbed dose x Q(LET)
- Aimed to provide a measurement-based estimate of the biological effectiveness of the radiation

RAD Dose Rate Measurements – Evolution throughout the Solar Cycle

- QF <Q> of radiation is affected by solar modulation
- Energy- & particle-type dependent



Ratio of Near Solar Max / Solar Min



- Main impact of solar modulations on protons (Q = 1)
- More lower-energy protons in solar min
- As a result <Q> is lower in solar min

RAD Dose Rate Measurements – Evolution throughout the Solar Cycle

- While ***absorbed dose*** increases by ***50%***, **<Q>** decreases by ***25%***
- As a result, ***dose equivalent*** on Mars only increased by ***13%***
- … ***13-30%*** for a sample Mars reference mission with transit

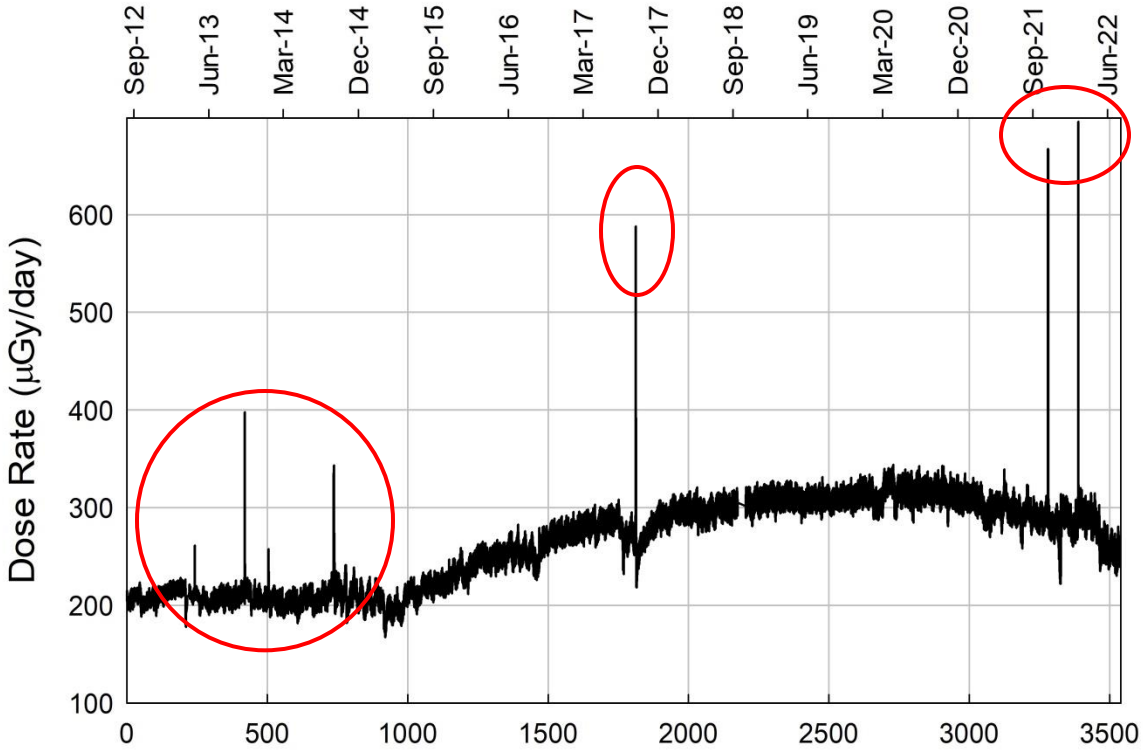
Quantity	Solar minimum of Cycle 24/5 (measured from 28 Nov 2019 to 3 October 2020)	Near solar maximum of Cycle 24 (measured from 7 August 2012 to 1 June 2013)	Ratio of solar minimum / near solar maximum of Cycle 24
Absorbed dose rate	0.314 mGy/d	0.21 mGy/d[a]	1.49
Average quality factor < Q>	2.3	3.05[a]	0.75
Dose equivalent rate	0.72 mSv/d	0.64 mSv/d[a]	1.13
500 days of Mars surface mission	0.36 Sv	0.32 Sv[a]	1.13
2 × 180 days of transit Earth – Mars	0.64–0.80 Sv	0.57 Sv[b]	1.13–1.40
Total mission dose equivalent (excluding SEP contributions)	1–1.2 Sv	0.9 Sv[a,b]	1.13–1.30

Results from Ehresmann et al. (2022), Icarus (in press).

- Note: Results are based strictly on RAD measurements & don't consider stay in bases, astronaut suits or skin doses

RAD Dose Rate Measurements during the MSL mission

- Occasionally, ***SEP events*** can dominate the dose rate (red circles)
- Increases usually on the order of hours to days
- RAD has directly observed ***7 SEP events*** so far



- The two strongest events were seen in ***Oct '21 & Feb '22***: ascending phase of ***solar max***

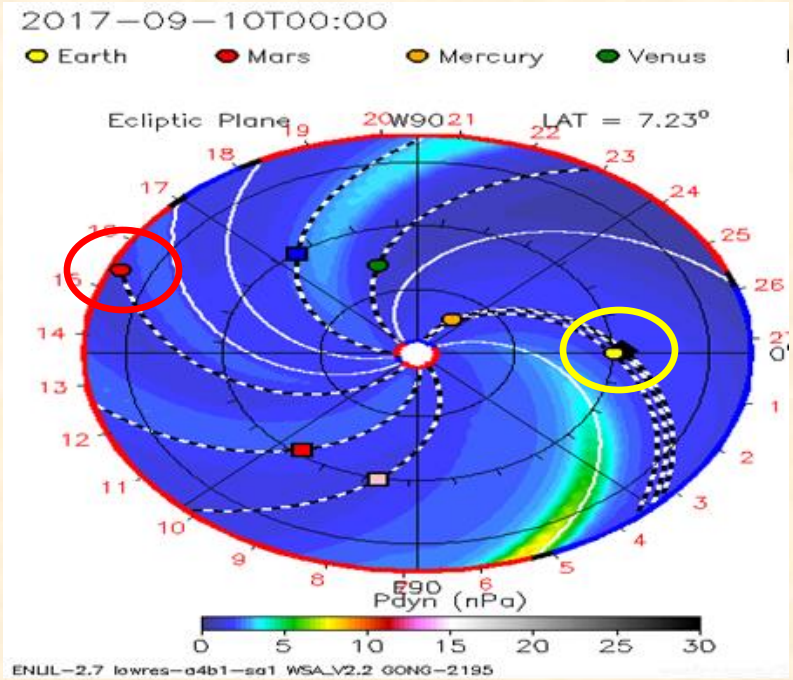
RAD Solar Particle Event Measurements

- Measuring effects of SEP events at Mars is crucial for space weather & human exploration

- In particular, when Earth & Mars are magnetically well-separated!

- RAD can answer the following questions:

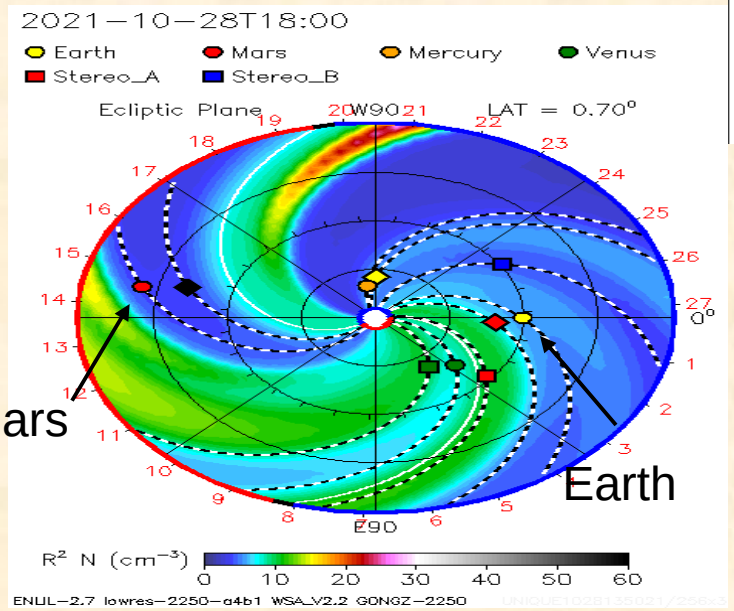
- How much dose did the event deliver?
  - …on the surface of Mars behind ~20 g/cm^2 shielding
- What is the timing of the event?
  - onset time, peak time, duration…
- How did the particle spectra change during the event
  - intensity, temporal evolution…

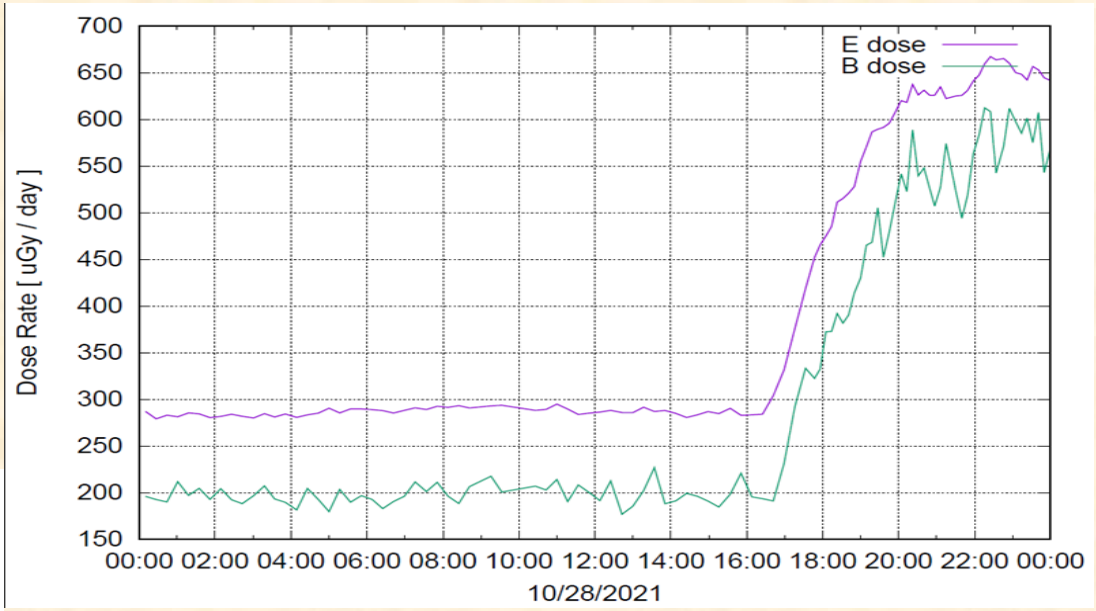


Planetary locations during the Sep 2017 event

The 28 October ‘21 Event seen by RAD

- On Oct 28 2021 the sun emitted an ***X1 flare*** at ~ 15:17 h UTC, followed by a ***halo-CME***
- Earth & Mars were separated by ***~180°*** … yet the event was still seen at both planets

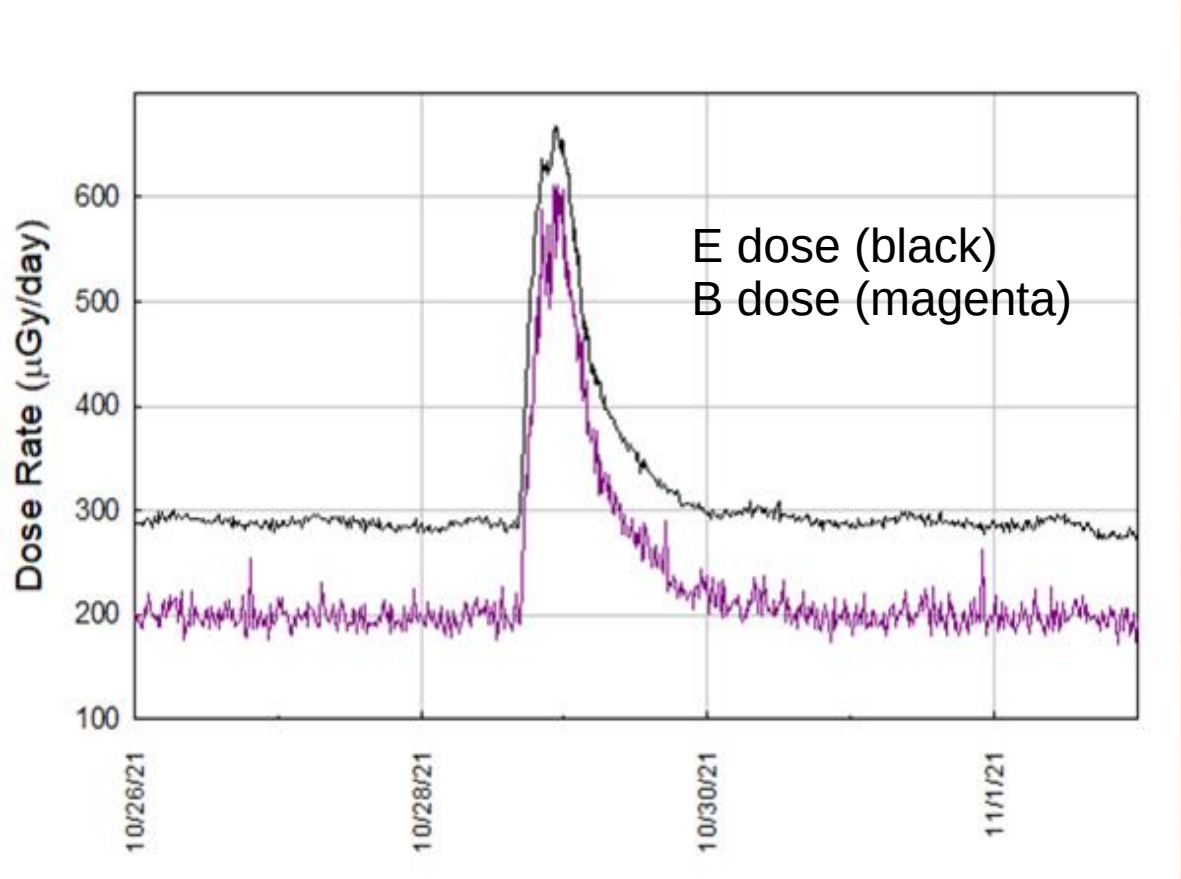




- Earth & Mars were both connected to the ***flanks*** of the CME
- Increase in dose at Mars ***~17 – 18 h UTC***
- At Earth, seen around the same time
- Earliest increase seen by Stereo-A (best connection to nose of CME)

The 28 October '21 Event seen by RAD

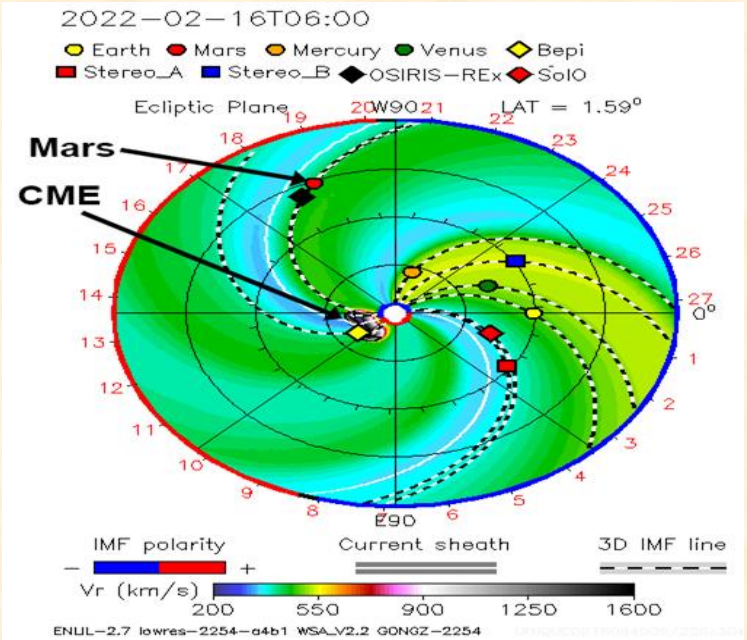
- On Mars, peak at ~ 22-23:30 h UTC
- Pre-event levels reached: morning of 30 Oct
- Peak dose (E) increase: x2.25 to 670 µGy/day
- Increase in B slightly higher (x3)

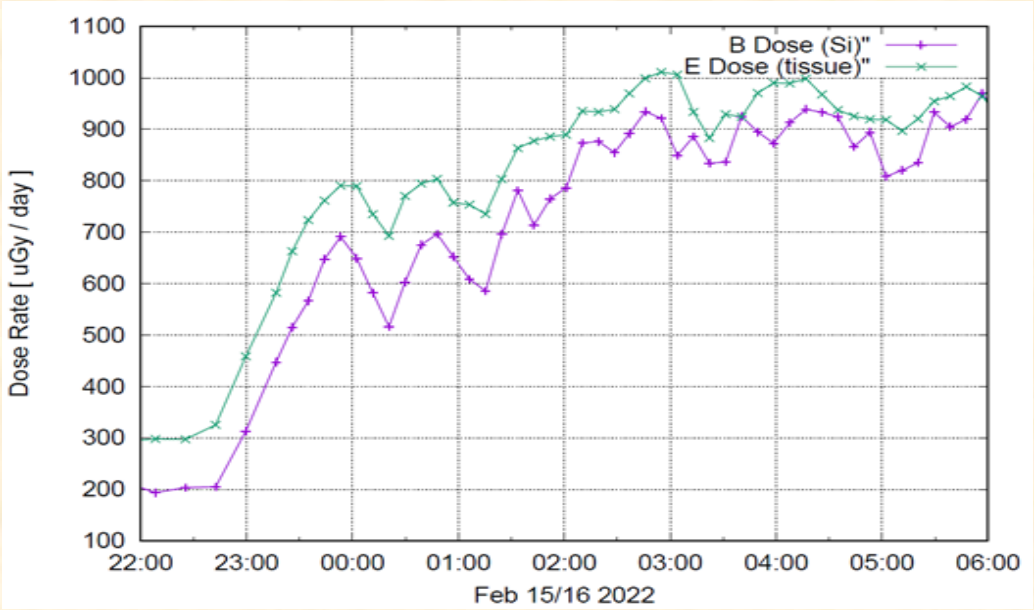


- The event delivered ~ 1 day's worth of GCR background dose: ~0.2 mGy in Si (RAMIS saw 2.2 mGy in Si Earth's orbit)

The 15/16 February ‘22 Event seen by RAD

- Massive, far-side CME released on 15/16 Feb 22
- Earth & Mars were separated by ***~135˚***
- Event was seen by RAD but not at Earth

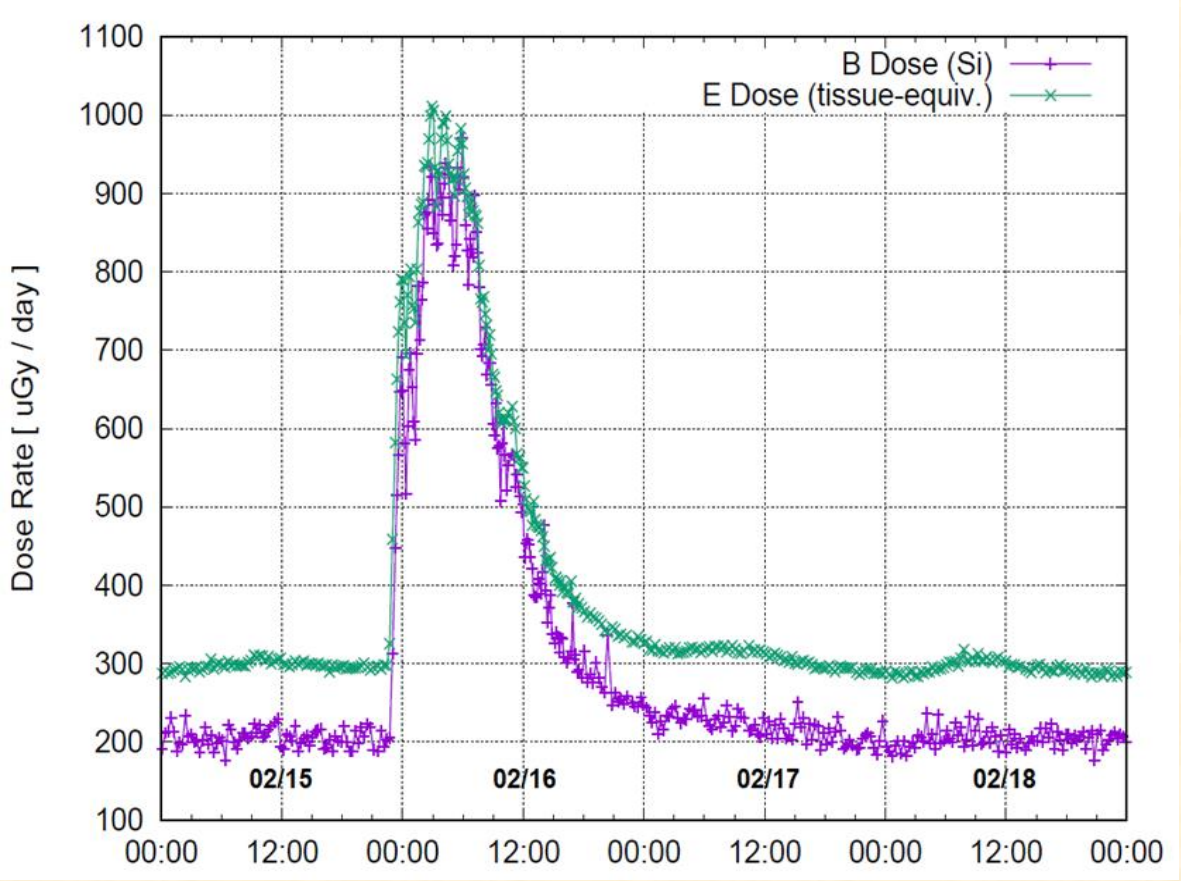




- Mars connected to the flank of the CME
- Increase in dose at Mars ***~23 h UTC*** (15 Feb)
- RAMIS only saw small increase in counts
- Seen or detected by other spacecraft (PSP, Bepi, SolO)

The 28 October ‘21 Event seen by RAD

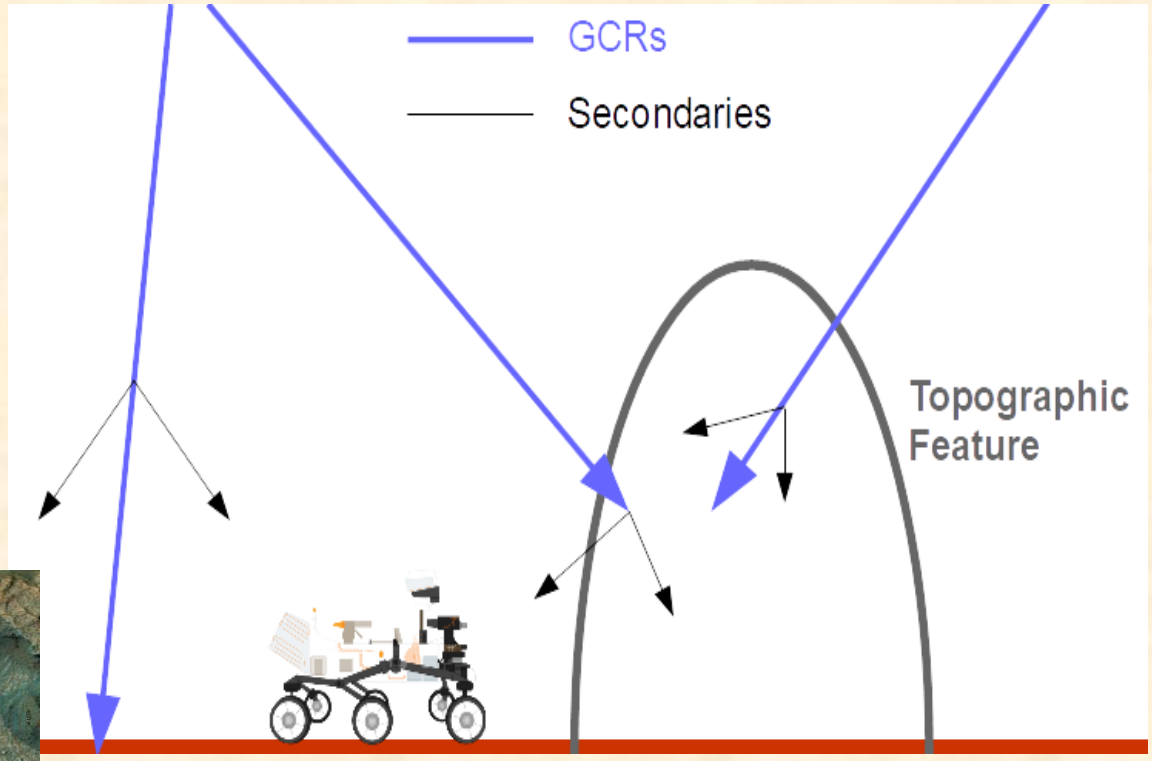
- RAD pek period: 2 – 6 h UTC (16 Feb)
- Pre-event levels: 17 Feb ~ 12 h UTC
- Peak dose (E) increase: x3.4 to 1 mGy/day!
- Increase in B higher (x4.5 – 5)

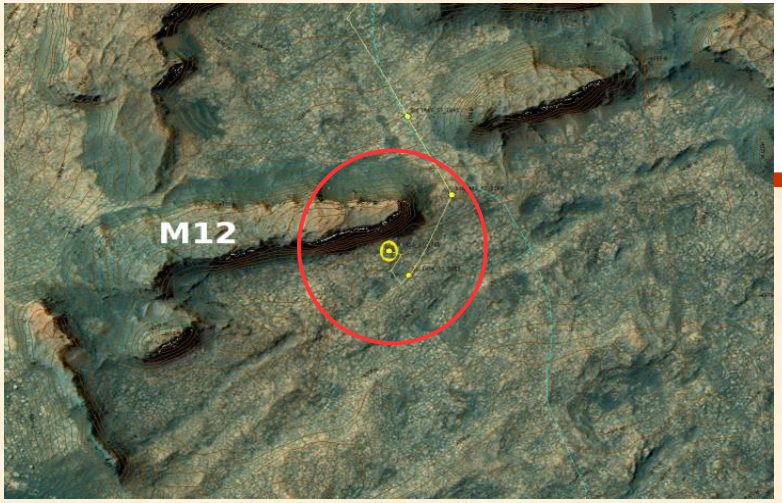


- The event delivered ~ 1.5-2 days worth of GCR background dose: ~0.35 mGy in Si

Regolith Shielding by Topography

- Natural terrain on Mars can serve as shield to reduce radiation dose
- Incoming GCRs can lose energy in the rock formation
- Overall net decrease in dose

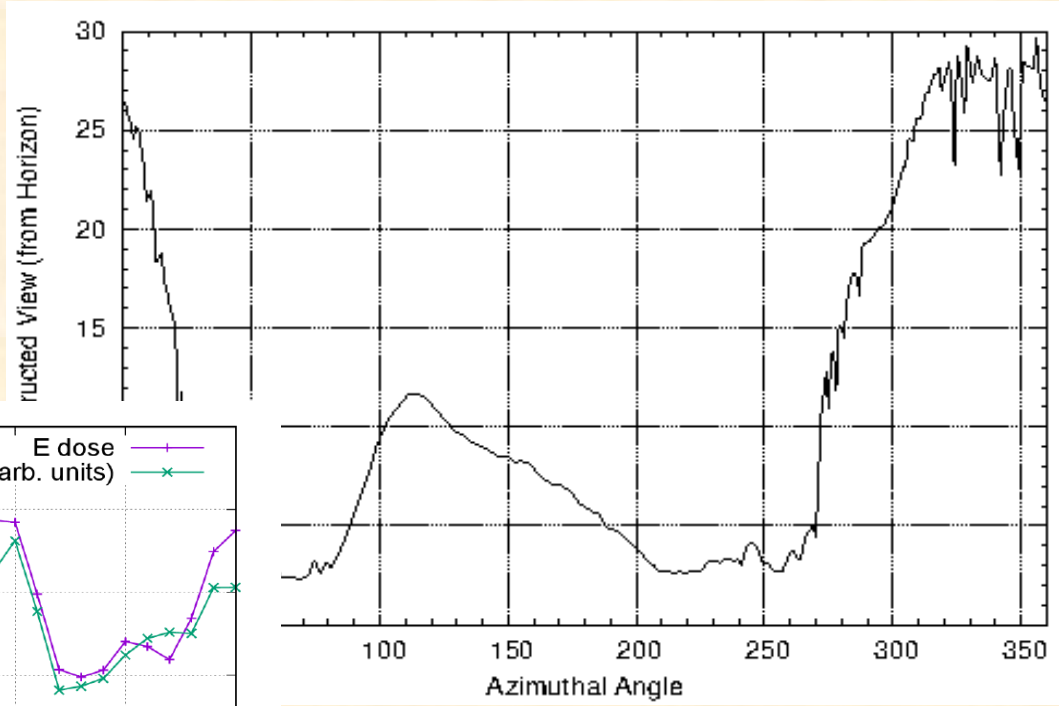




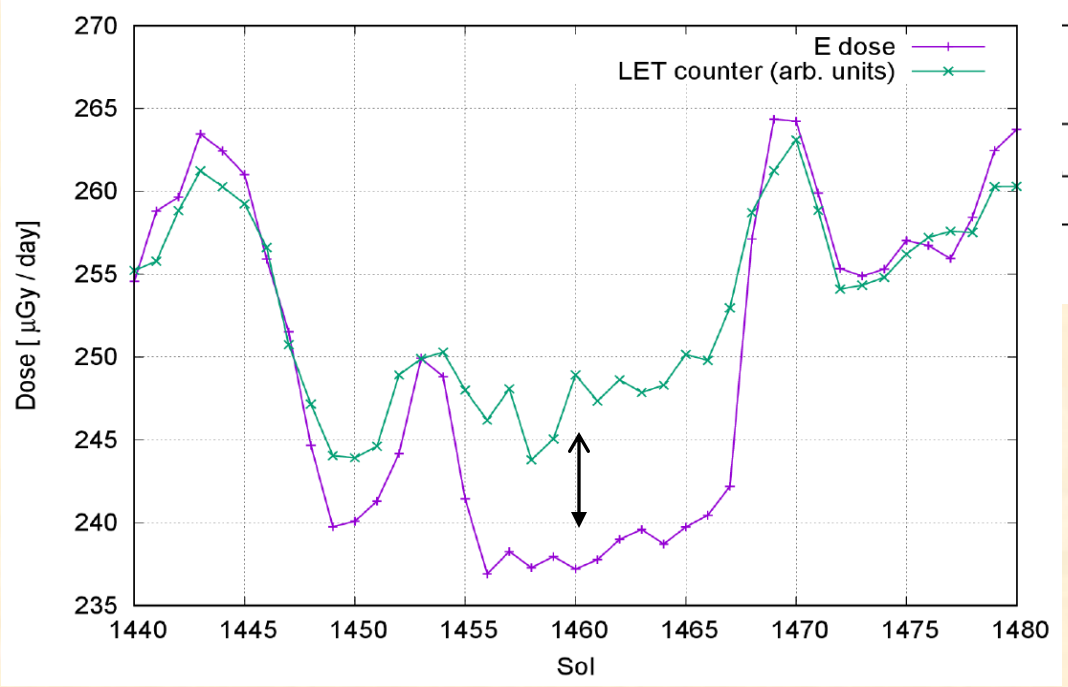
- RAD observes this effect when driving / parking close to topography shielding out parts of the sky

First Proof of Radiation Shielding on Mars at Murray Buttes

- First observed when RAD parked near the Murray Butte
- The butte blocked out 19% of the sky around RAD



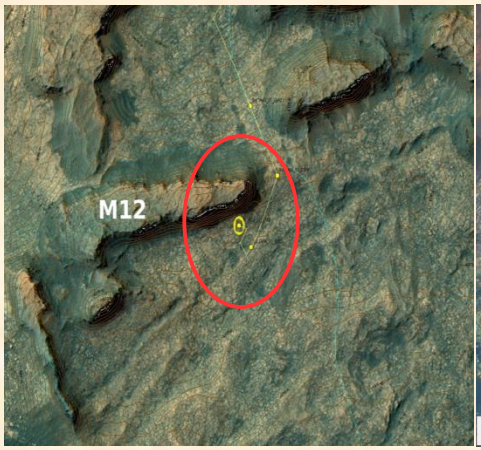
Angle of obstruction around RAD at Murray Butte



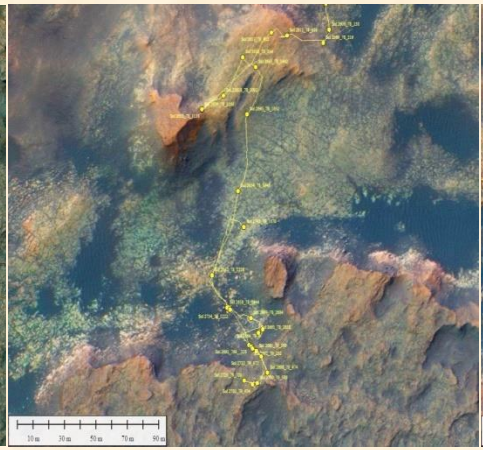
- 4-5% decrease in dose rate & 7.5% in neutral particles

Radiation Shielding on Mars by Natural Terrain

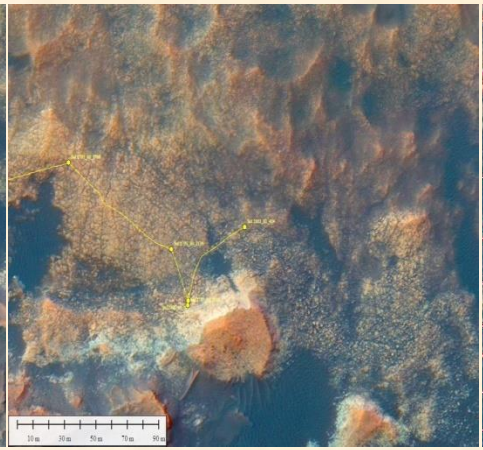
- We find this effect whenever, RAD is near obstructing topography



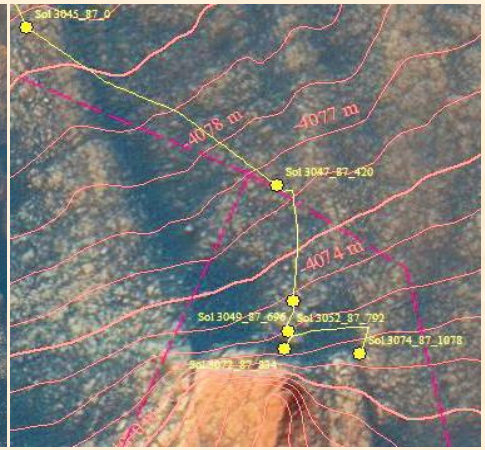
Sols 1456-67: Murray Butte M12.
Average angle of obstruction: ~ 11°.
Dose decrease: ~4-5%



Sols 2658-92 & 2734-42: Tower Buttes area.
Average angle of obstruction: ~ 6-8.5°.
Dose decrease: ~3%



Sols 2798-2802: Bloodstone Hill.
Average angle of obstruction: TBD.
Dose decrease: ~5%



Sols 3050-3090: Mt Mercou area.
Average angle of obstruction: multiple instances, including highest-to-date.
Dose decrease: >8-10%

- The amount of shielding effect depends on both the obstruction in the vertical and azimuthal

- Taken together, we can determine how much of the 2π sky was blocked out & what the average angle (in the zenith) of obstruction was

RAD Acknowledgments

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