The Mars Science Lab Radiation Measurements during Cruise and on the Surface on Mars

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On behalf of the MSL-RAD Science Team

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DLR

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RAD Science Team

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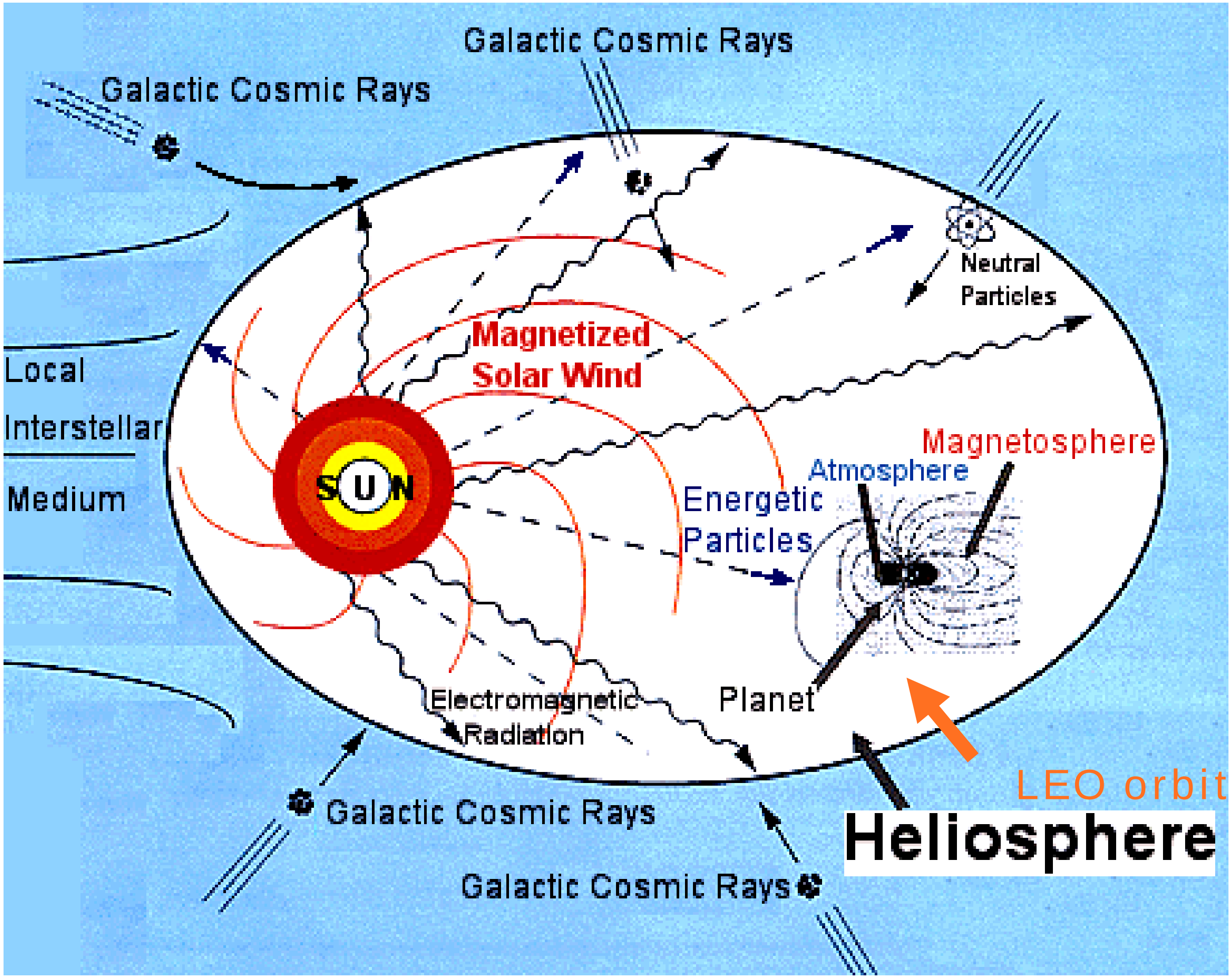
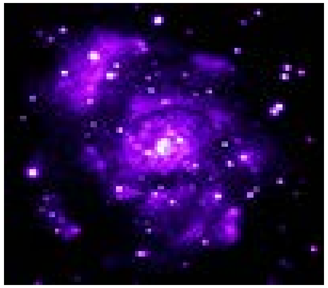
Radiation Field in the Heliosphere

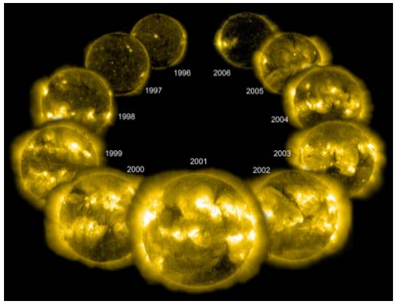


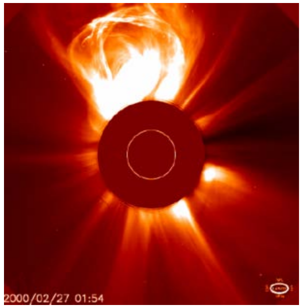
Radiation Environment



GALACTIC COSMIC RAYS

- Originates outside the solar system
- Modulation with solar cycle
- Fully charged atomic nuclei (^{1}H to ^{238}U)
- Isotropic
- Extremely high energy
  - Very penetrating,
  - Hard to shield,
  - Biologically highly damaging

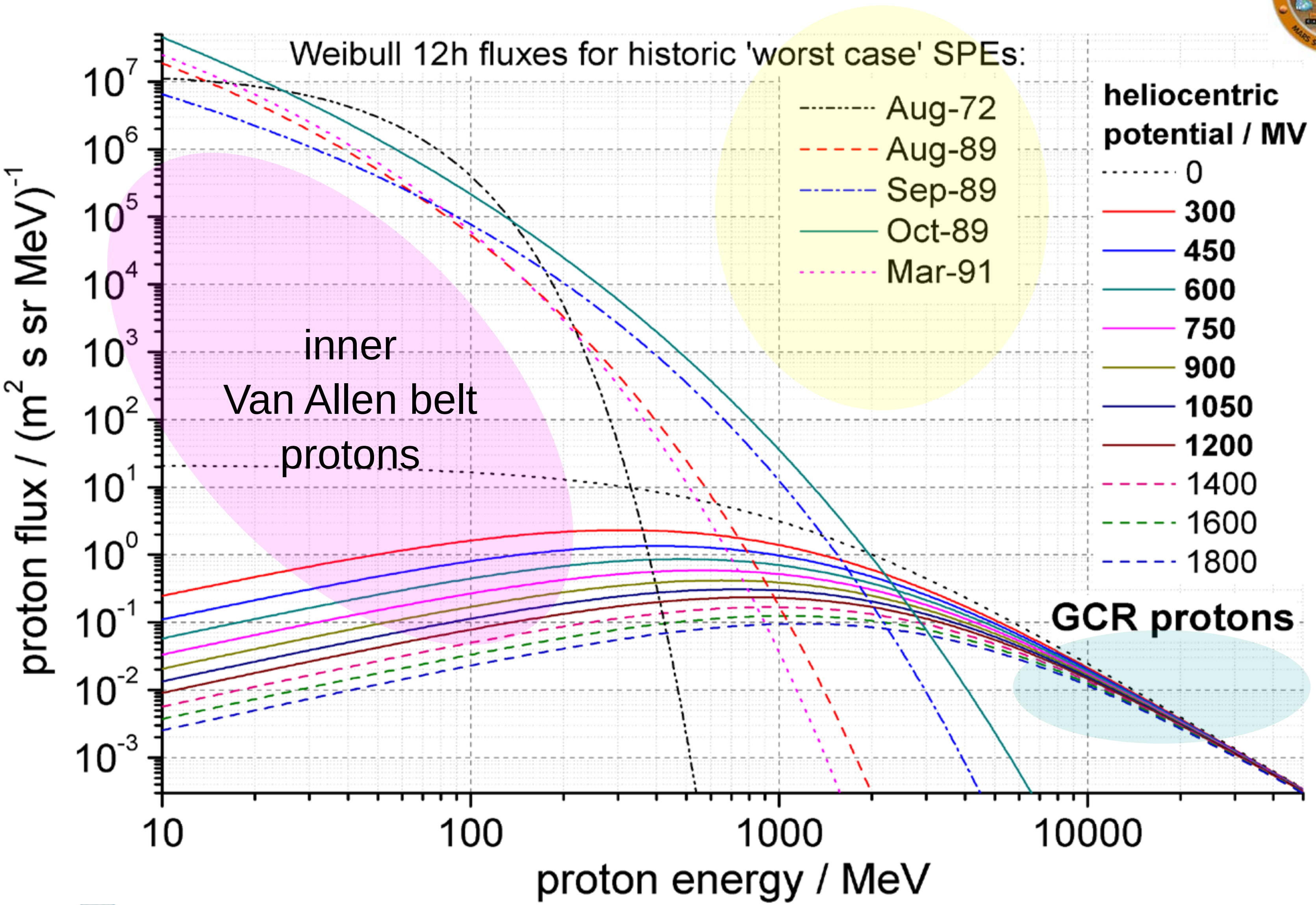




SOLAR COSMIC RAYS

- Solar particle events (flares, coronal mass ejections)
- Mostly protons, but ions of higher mass included
- Infrequent occurrence
- Highest probability at solar maximum
- directional to isotropic
- Alert time about 20 min
- Dose increase by up to a factor of 1,000

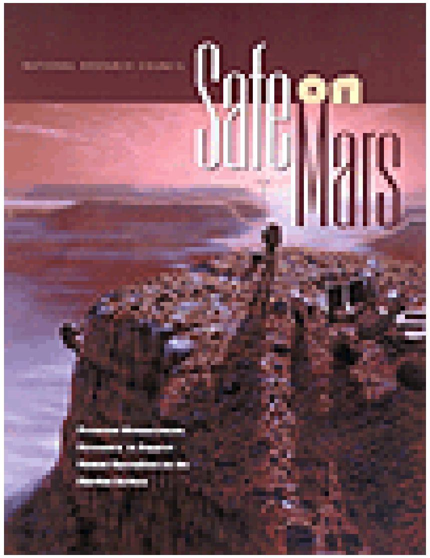
Fluxes of primary space radiation components



Investigation Background

NRC/NAS “*Safe on Mars*” Radiation Recommendation May 2002

- In order to validate the radiation transport codes, thereby ensuring the accuracy of radiation dose predictions, NASA should perform experiments to **measure the absorbed dose in a tissue-equivalent material on Mars at a location representative of the expected landing site**, including altitude and bulk elemental composition of the surface
  - The experiment should distinguish the radiation dose contribution induced by charged particles from that induced by neutrons
  - **These experiments should be made a priority in the Mars exploration program**



Precursor Measurements Necessary to Support Human Operations on the Surface of Mars

DLR

NASA

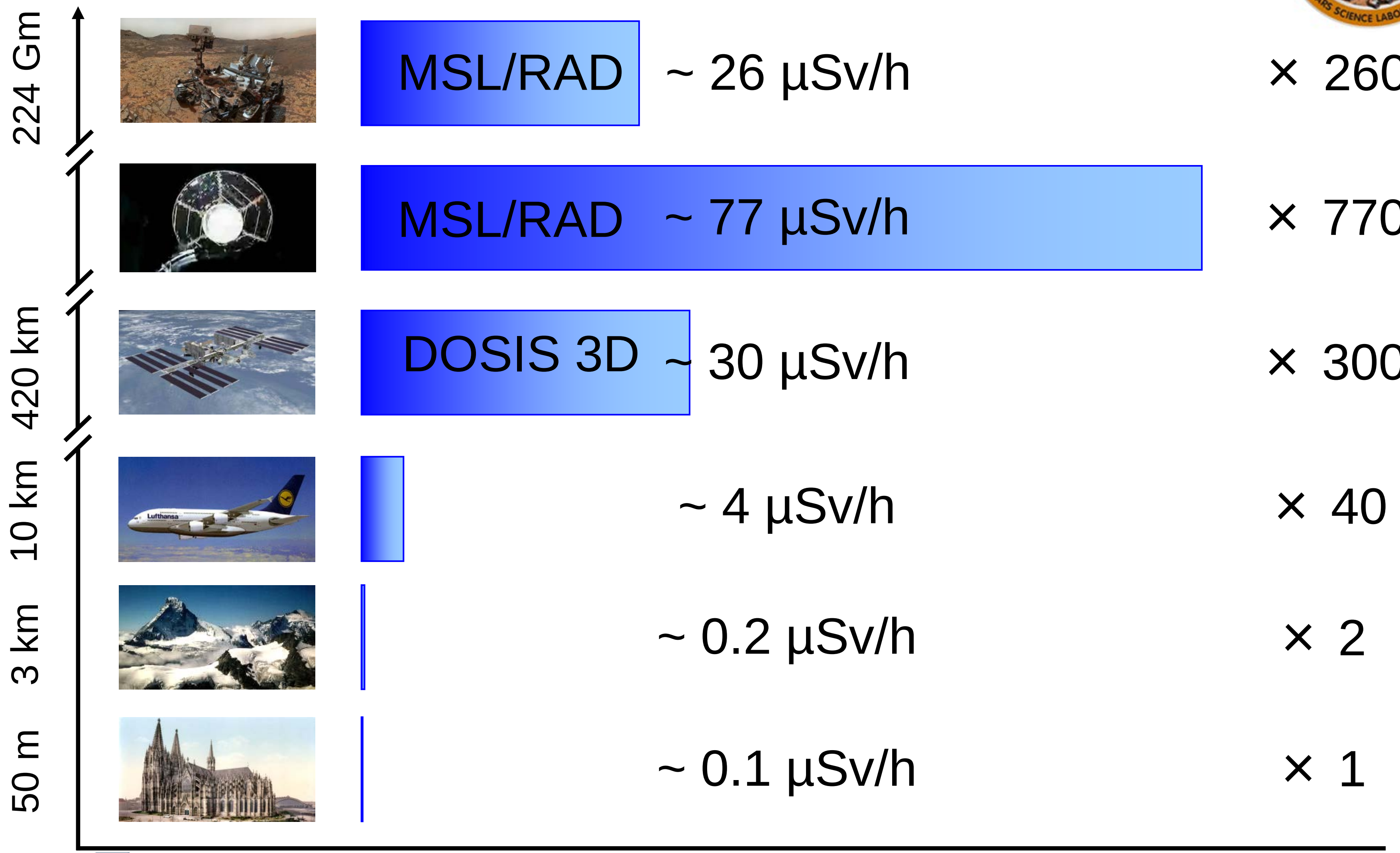
C A U

Investigation Background

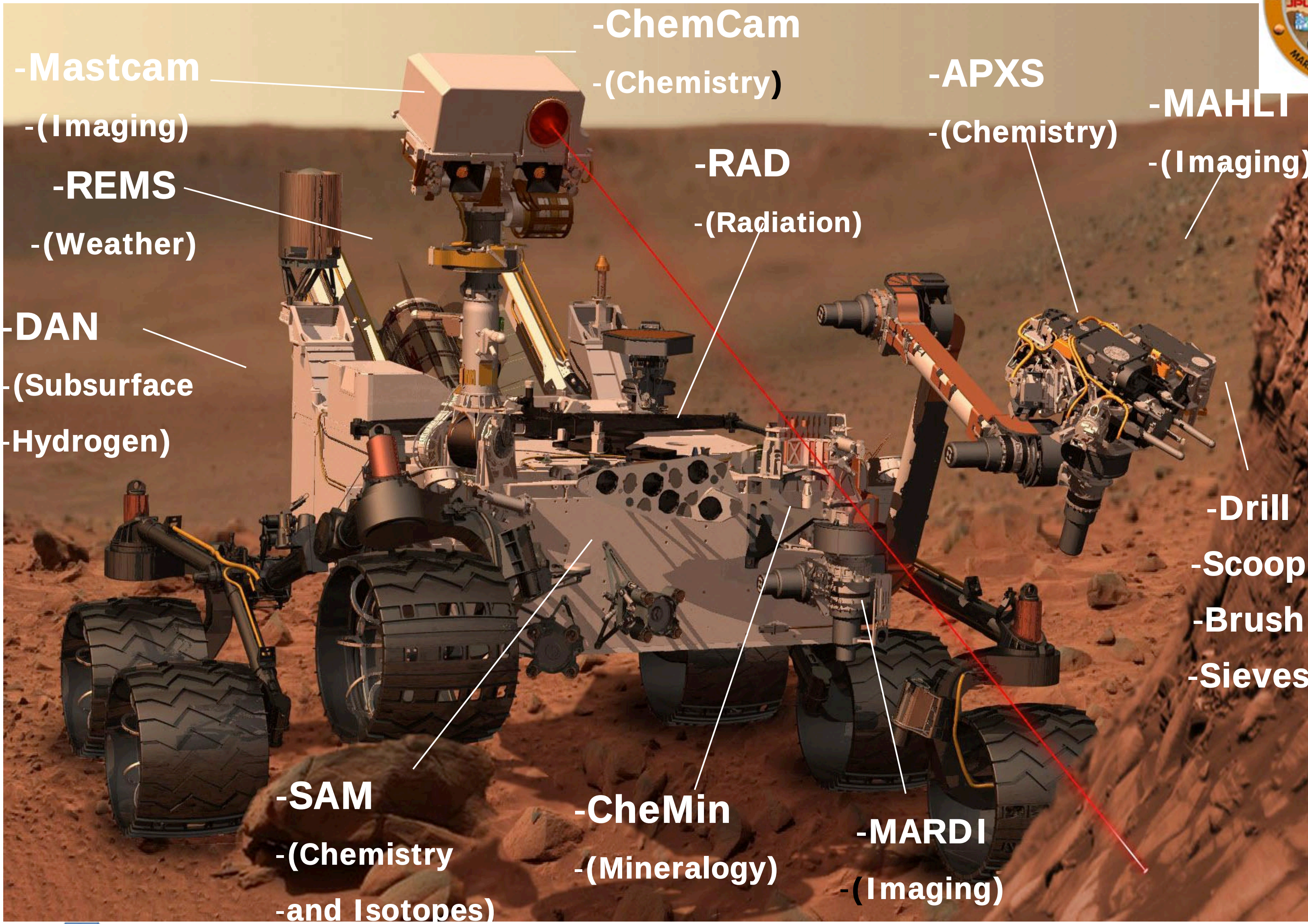
NASA *Living With a Star* Radiation Workshop Recommendations (April 2004)

- Radiation data collected on the surface of Mars are required for projecting crew health risks and designing protective surface habitats:
  - Surface measurements of dose, dose equivalent, and LET spectral components from GCR protons, high-charge and energy (HZE) ions, and neutrons
  - Determine individual contributions from protons, HZE's, and neutrons to LET spectra including charge spectral data
- Multiple measurements are preferred to characterize temporal and spatial variations
  - Solar Minimum and Solar Maximum
  - Atmospheric and Surface Variations

Radiation Exposure



Curiosity's Science Payload



RAD Primary Scientific Objectives

- Characterize the energetic particle spectrum incident at the surface of Mars, including direct and indirect radiation created in the atmosphere and regolith.
- Determine the radiation Dose rate and Equivalent Dose rate for humans on the Martian surface.
- Validate Mars atmospheric transmission models and radiation transport codes.
- Determine the radiation hazard and mutagenic influences to life, past and present, at and beneath the Martian surface.
- Determine the chemical and isotopic effects of energetic particles on the Martian surface and atmosphere.

A Brief History

- RAD was selected for MSL in 2004.
- Moderately shielded environments are highly pertinent to human flight.
  - ~ 16 g cm-2 spacecraft shielding during cruise
  - ~ 20 g cm^{-2} CO_2 shielding on Mar.
- MSL launched Nov. 2011, arrived Aug. 2012.
- RAD operated during the complete cruise.
- RAD is approaching 1000 “sols” of operations on Mars.
- Sol = Martian day = 1.02 Earth day
- 687 Earth days = 1 Mars year

The Radiation Assessment Detector (RAD)

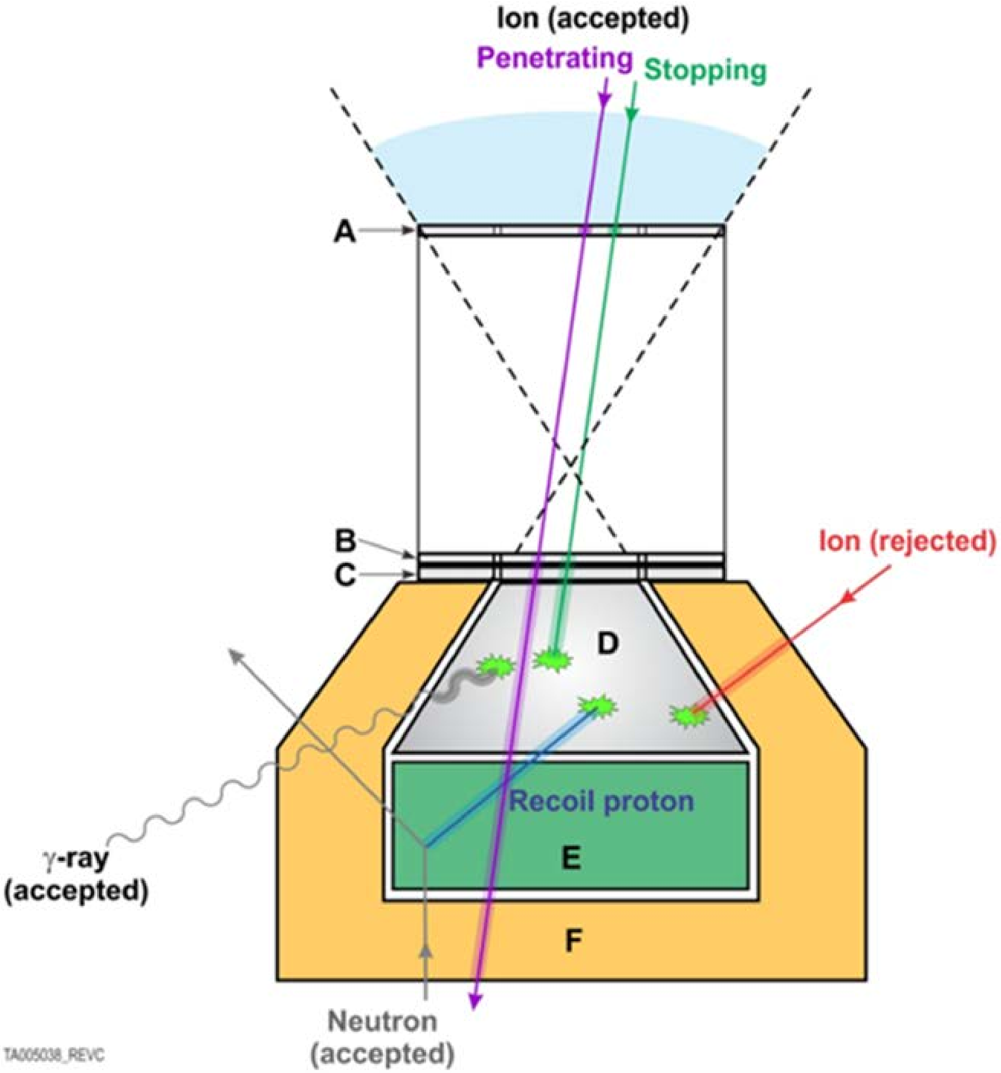
- RAD is a compact, highly capable radiation analyzer to characterize the full spectrum of space radiation (both charged & neutral particle).
- RAD can be used as an "area detector" inside a spacecraft, or as an "environment monitor" outside of a spacecraft to measure the space environment.
- During Cruise, inside the MSL spacecraft, RAD served as a proxy to validate models of the radiation levels expected inside a spacecraft that future astronauts might experience.
- MSL RAD is currently characterizing the radiation environment on the surface of Mars.

RAD Sensor Head Schematics & Measurement Capabilities

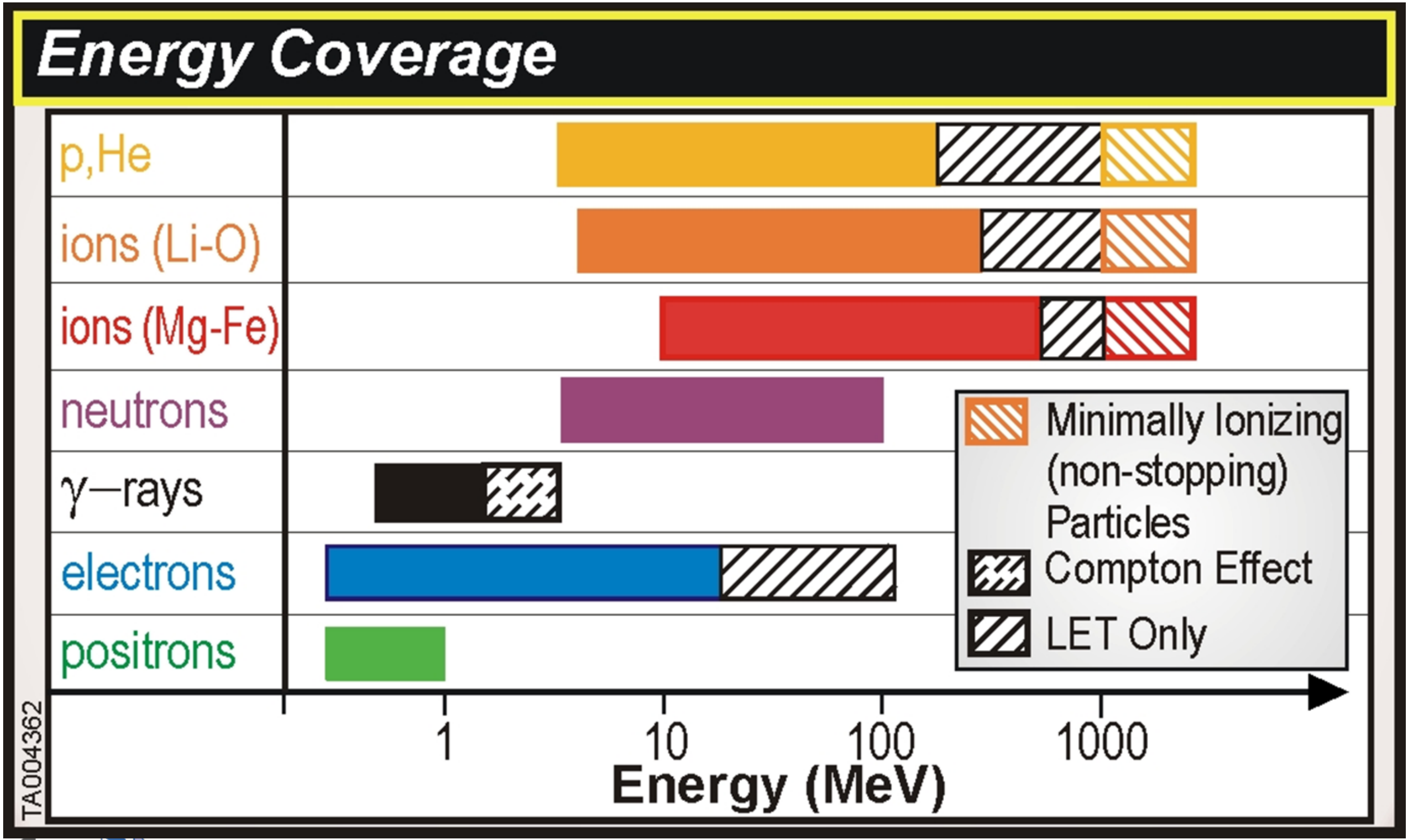
- 3-element silicon telescope (A, B, C).
- CsI scintillator (D).

  for γ-ray detection; stops protons and 4 He up to ~ 95 MeV/nuc.
- Plastic scintillators (E, F).

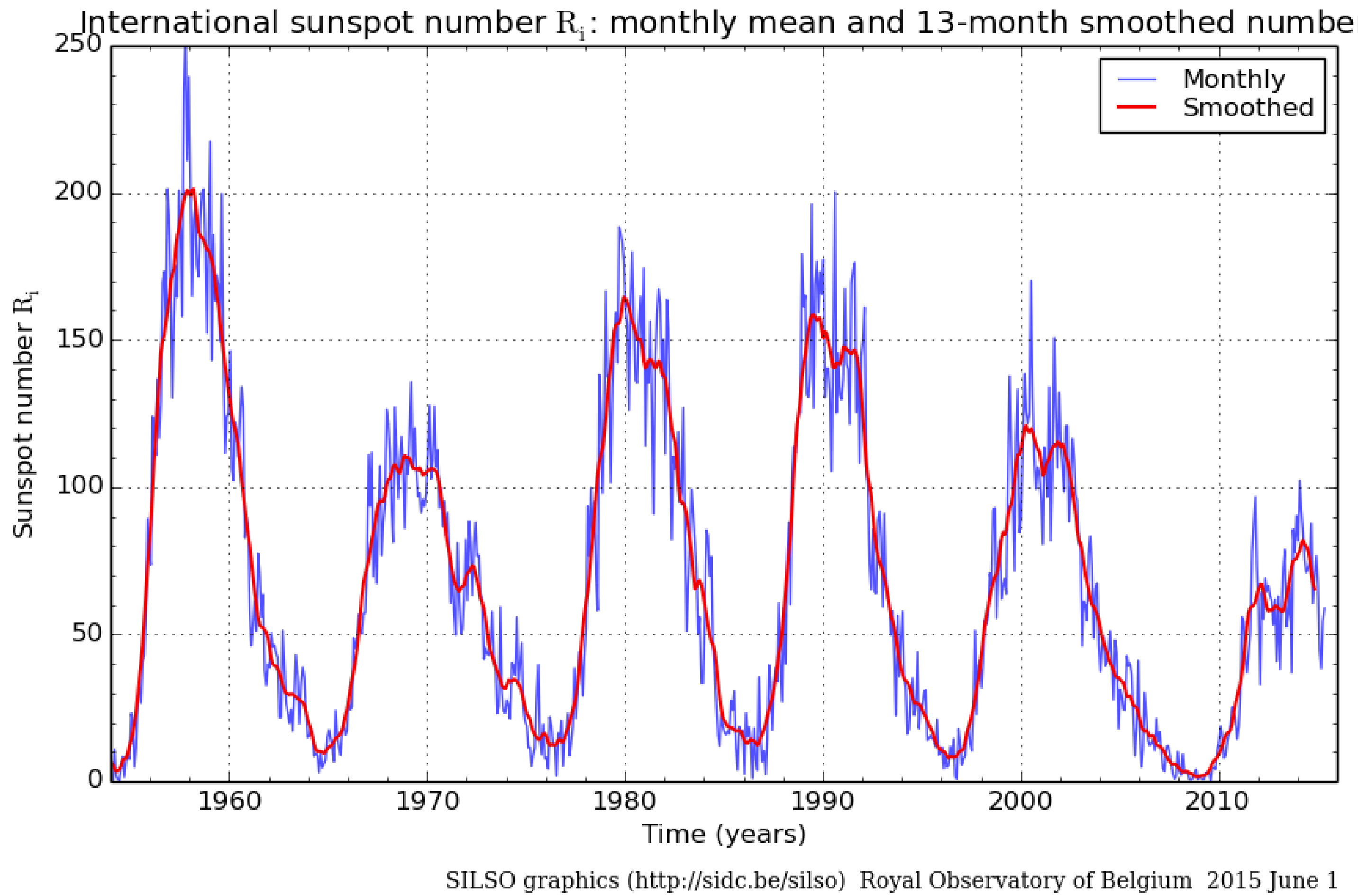
  F enables neutral particle detection in D (ɣ''s) and E (neutrons).



RAD Measurement Capability



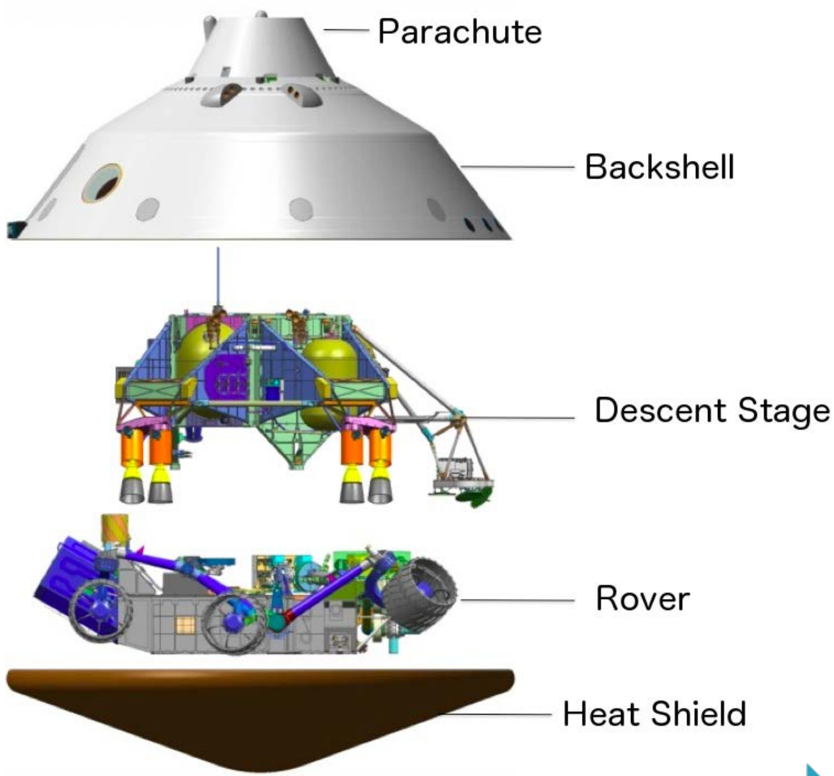
MSL-RAD and the Solar Cycle

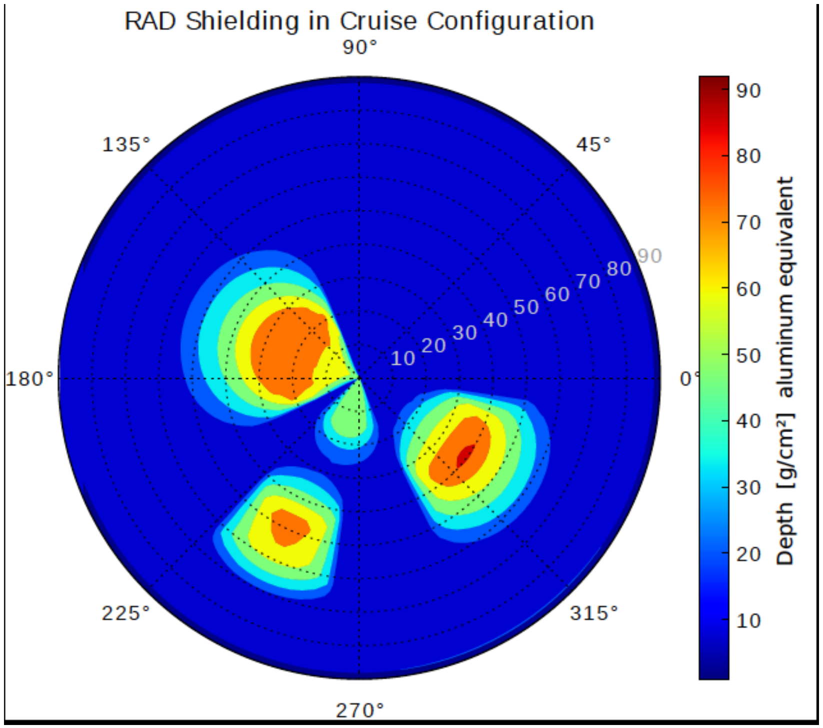


Cycle 24 is weakest in ~ 100 years (not predicted).

Cruise Data and Calculations

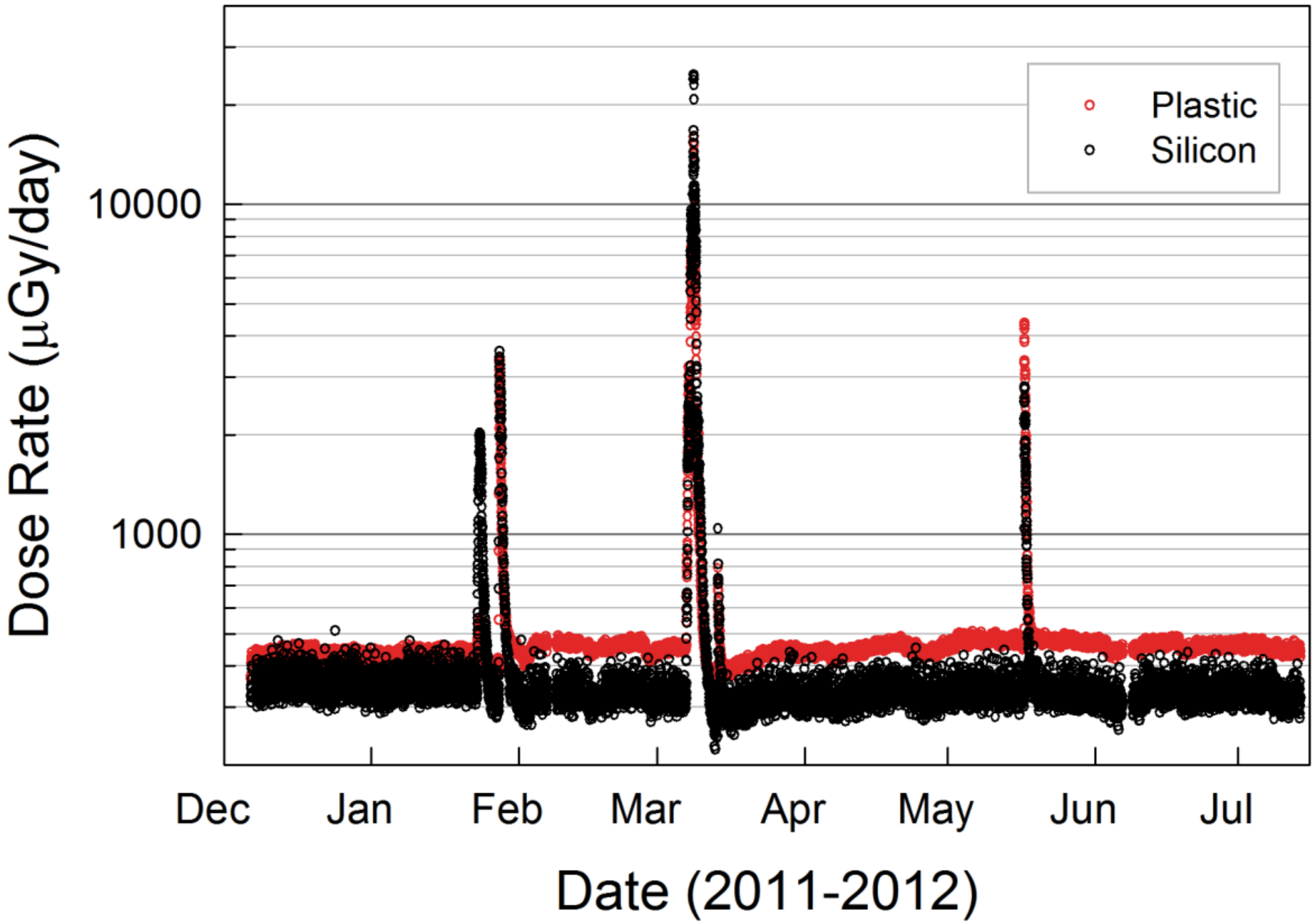
Cruise Configuration



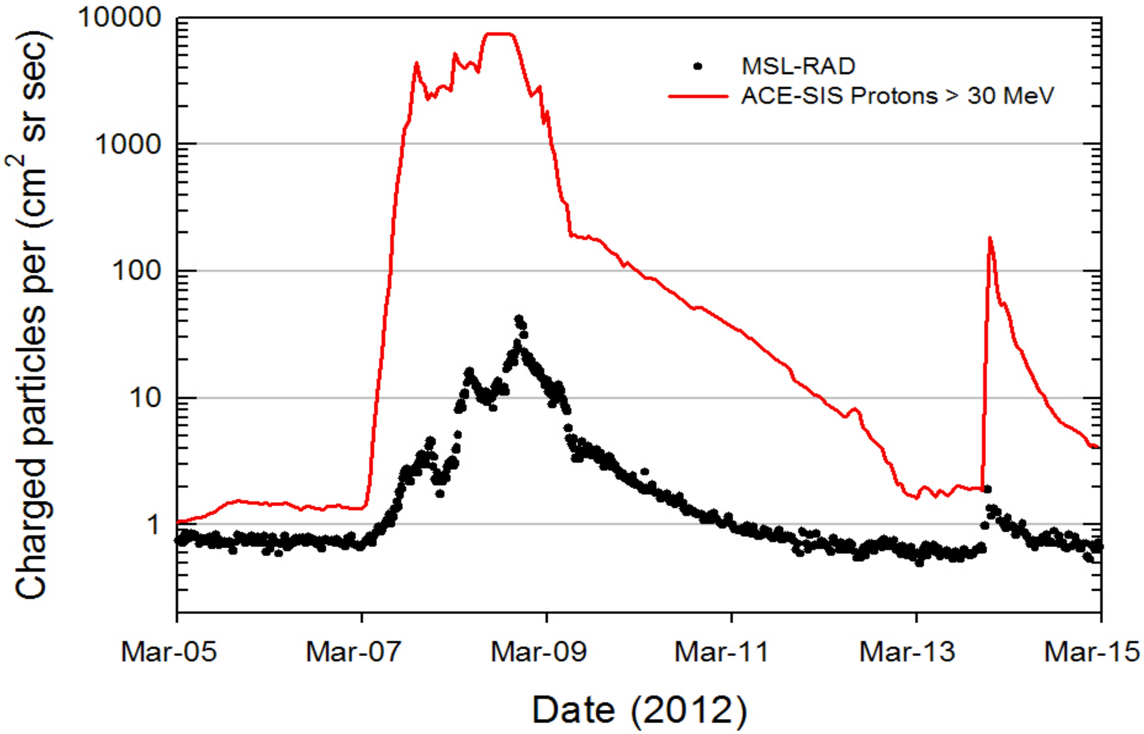


- Average shielding depth in 20° FOV cone ~ 16 g cm^{-2}
- ~ ½ of upper hemisphere lightly shielded.

Radiation Assessment Detector (Cruise Measurements)

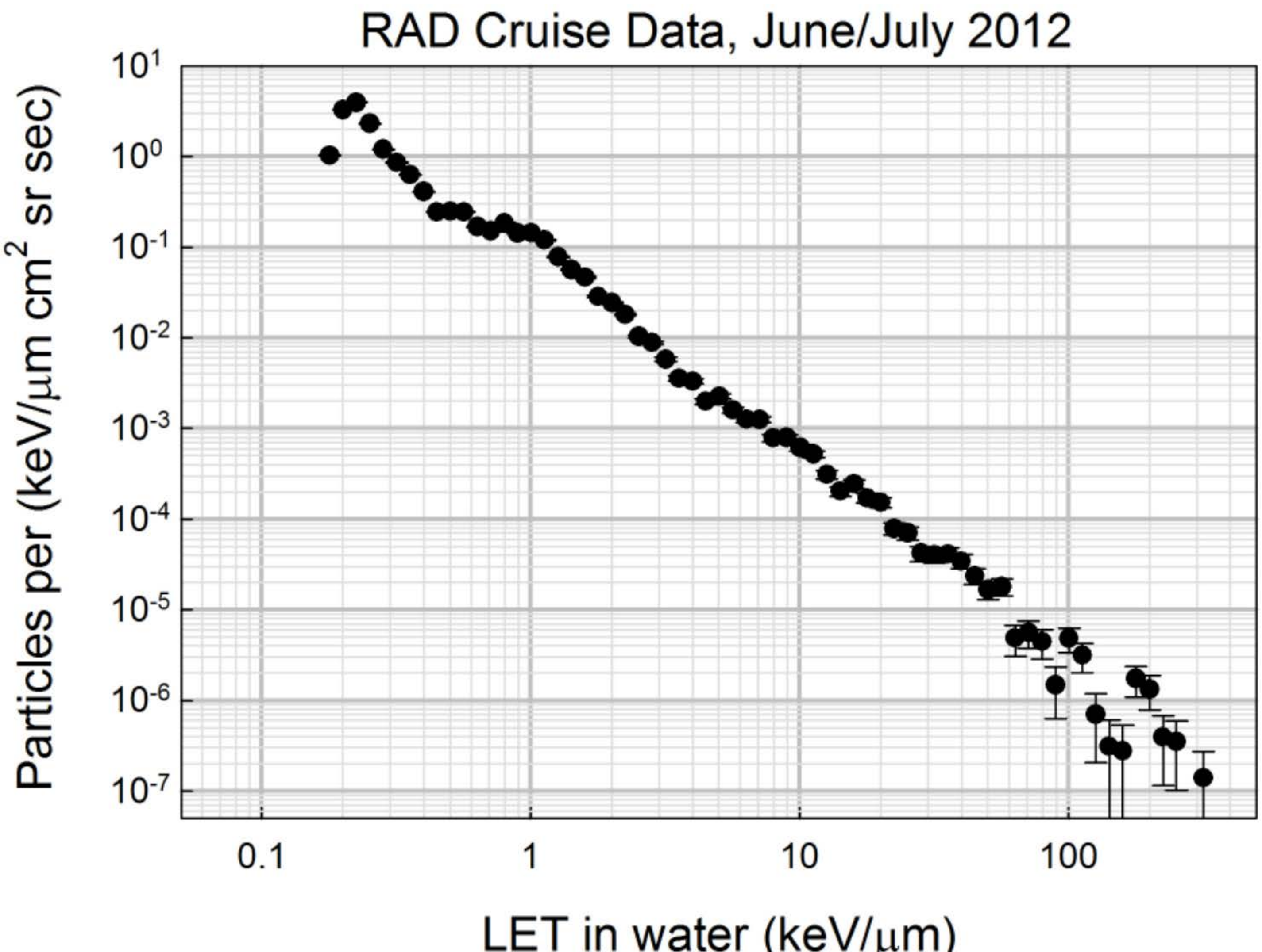


SEP Events in Cruise

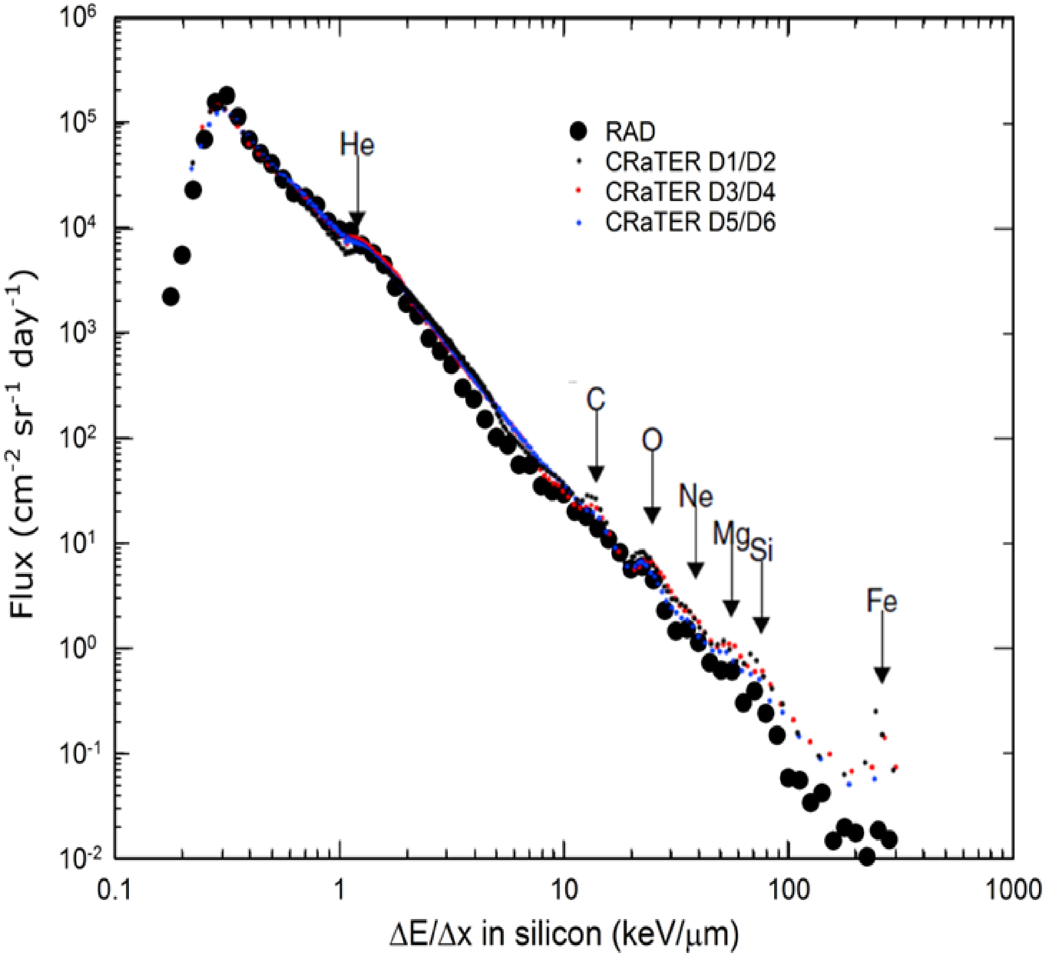


- Largest SEP event in cruise was 7 March 2012.
- Look at ACE/SIS data (unshielded) for comparison with free-space proton fluxes.
- Even the light shielding above RAD reduced peak flux by ~100x

RAD Measured LET Spectra during Cruise



MSL/RAD & LRO/CRaTER Comparison



- Compare silicon LET spectra (~21 g cm-2 CO_2 shielding) to LET spectra from CRaTER with 0.2, 6, and 9 g cm-2 shielding.
- RAD sees slightly more charge 1 particles and fewer heavies, as expected.

Radiation Environment Measured by MSL/RAD during cruise (GCR only),

RAD Measurement	Cruise	Units
Charged Particle Flux	0.64	particles cm^{-2} s^{-1} sr^{-1}
Fluence (A2*B)	3.98	cm^{-2} s^{-1}
Dose Rate	0.464 +/- 0.057	mGy/day
Avg. Quality Factor <Q>	3.82 +/- 0.3	(dimensionless)
Dose Equivalent Rate	**1.84 +/-0.30**	**mSv/day**

Hassler et.al, Science 2013

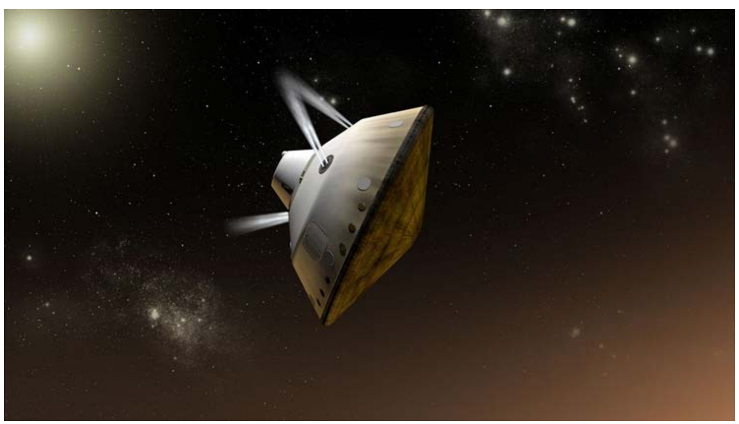
SEP Events Contribution to Total Dose During Cruise

Time Period (2012)	Integrated Dose Equivalent (mSv)
Total Jan 23-29 SEP	4.0
Total March 7-15 SEP	19.5
Total May 17-18 SEP	1.2
SEP Events Total	**24.7**
GCR average per day	1.84
TOTAL (GCR + SEP) (253 days)	**490**

-During Cruise, SEP Events contributed ~5% to the Total Integrated Dose Equivalent.

- However, SEP Fluences & Energy Spectra ("Hardness") are highly variable…
- *…a very large SEP Event or "Super-Event" (similar to the 1972 SEP event) could potentially contribute substantially more (>order of magnitude) to the total integrated Dose Equivalent.*

Calculations for the Cruise to Mars



<u>Interplanetary space</u>

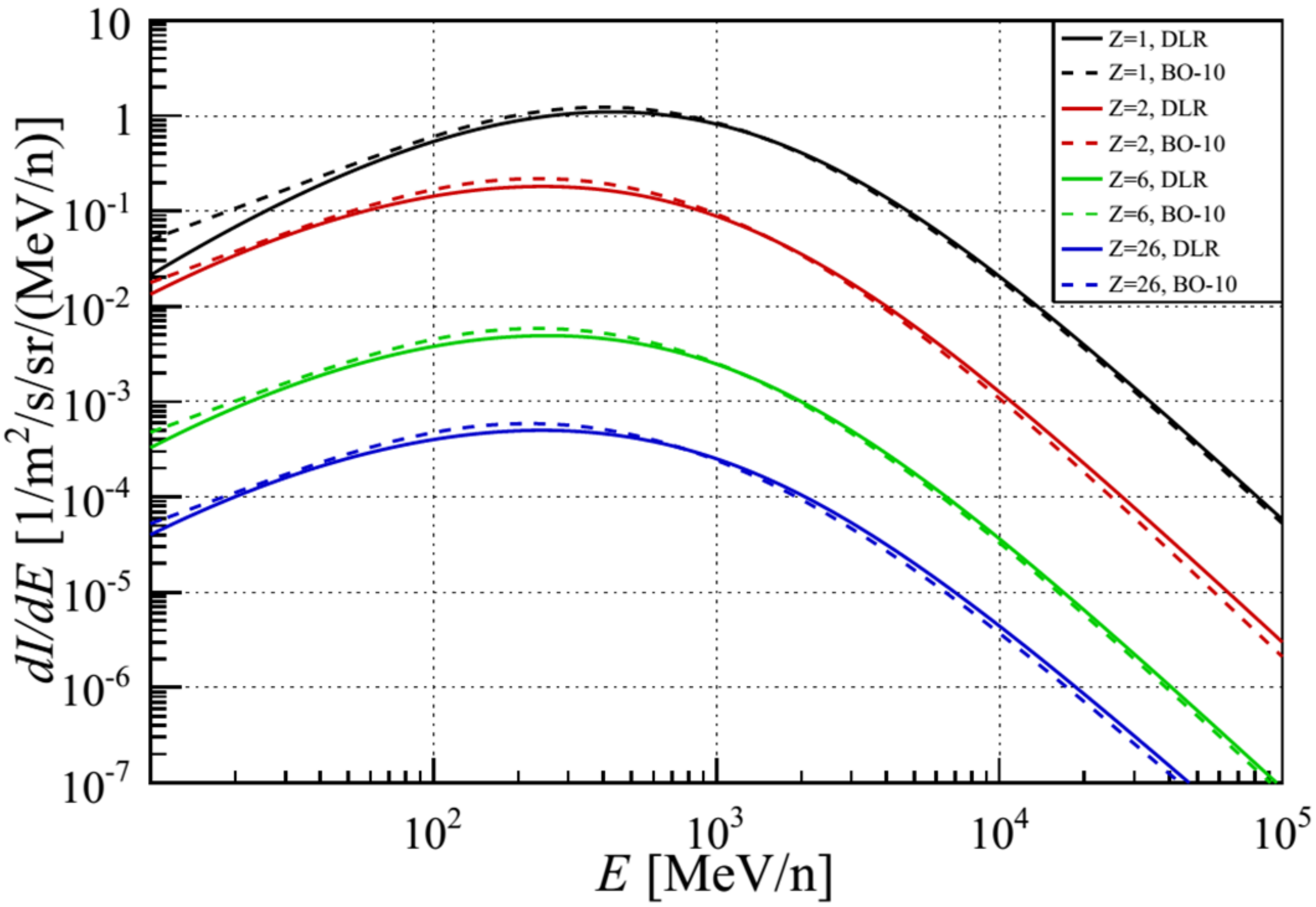
PLANETOCOSMICS
GEANT4.9.6.p02

Primary GCR:
- Z=1-26
- Solar maximum + MSL cruise
- 10 MeV/n ≤ E ≤ 200 GeV/n

Geometries:
- MSL-shielding distribution
- Varying spherical shielding

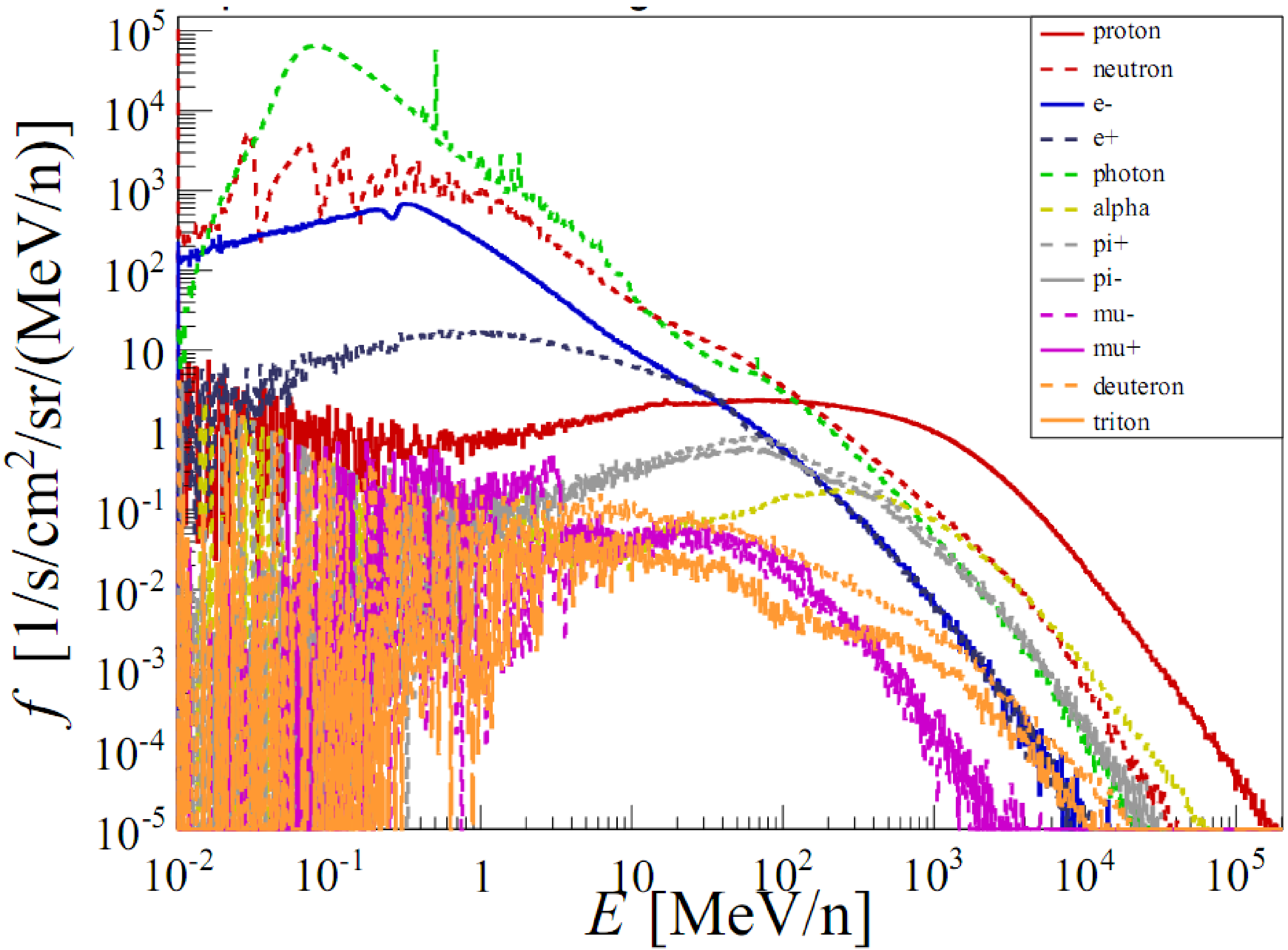
Results:
- Particle energy and LET spectra
- Dose rates, effective dose rates, organ dose rates

Primary GCR Spectra for the time between Aug 2012 and Jan 2013

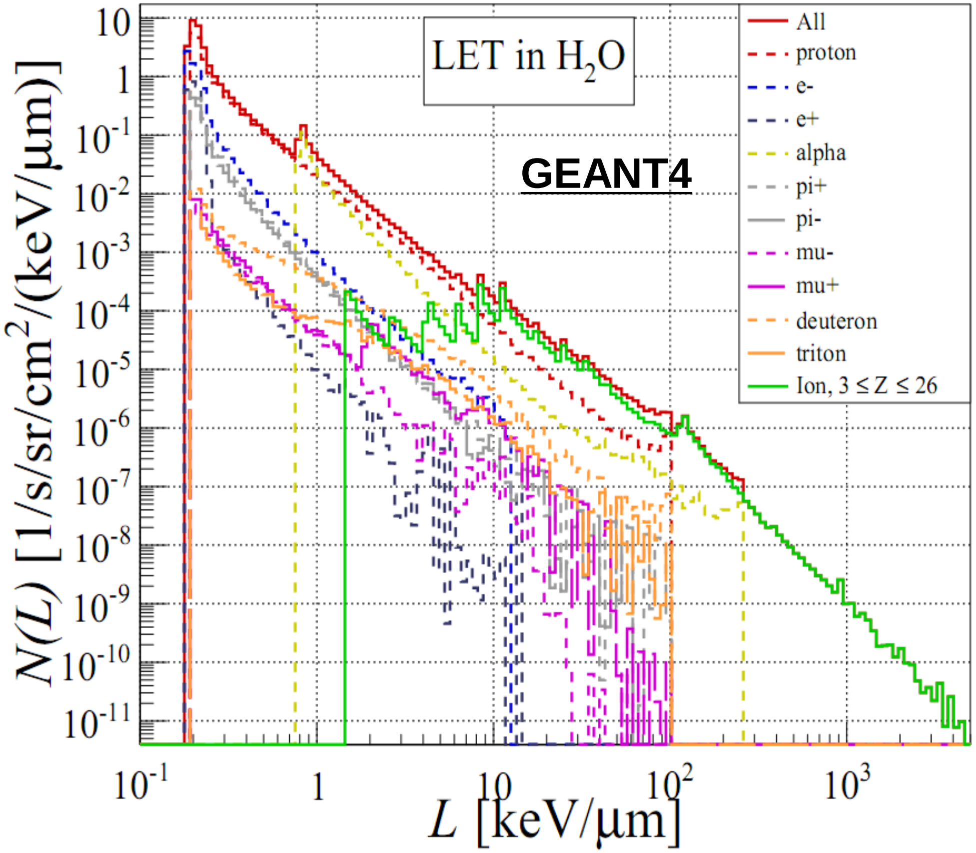


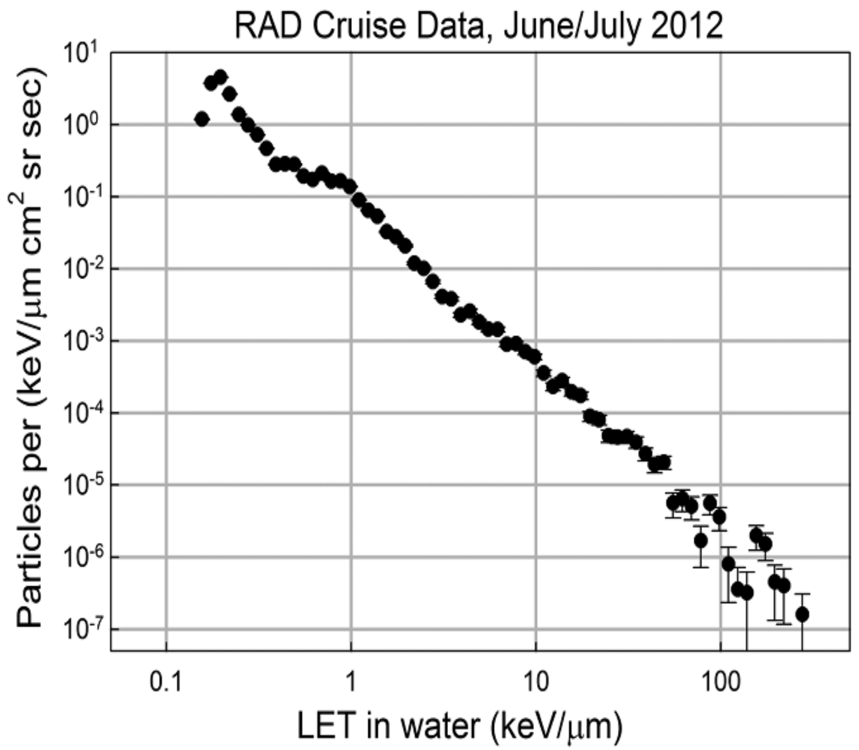
Matthiä et al., 2013 and Badhwar/O'Neill 2010 (BO-10) ,O'Neill, 2010

MSL-Cruise Energy Spectra seen by RAD



MSL- Cruise LET-spectra; Simulation and Measurements





Zeitlin et. al, 2013

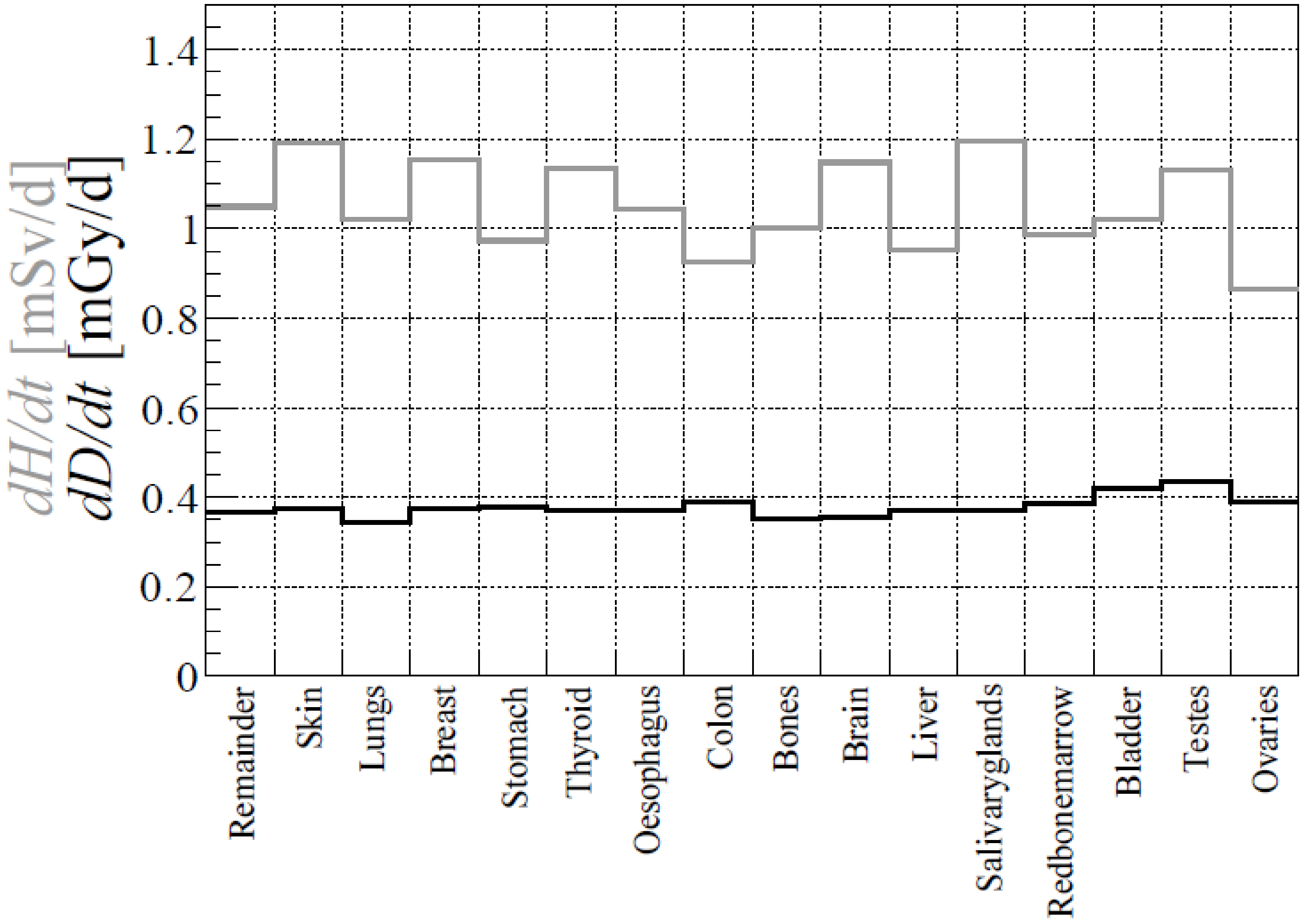
Measured and Calculated GCR Dose and Dose Equivalents

GCR Flux Model	Pions included in transport	Dose Rate (µGy/day)	Dose Equivalent Rate (µ Sv/day)	<Q>
Badwar O'Neill 1996	N	417	1.68	4.03
	Y	515	1.80	3.50
Badhwar O'Neill 2011	N	356	1.69	4.74
	Y	455	1.80	3.96
RAD Measurements		464 ± 57	1.84 ± 0.30	3.96 ± 0.30

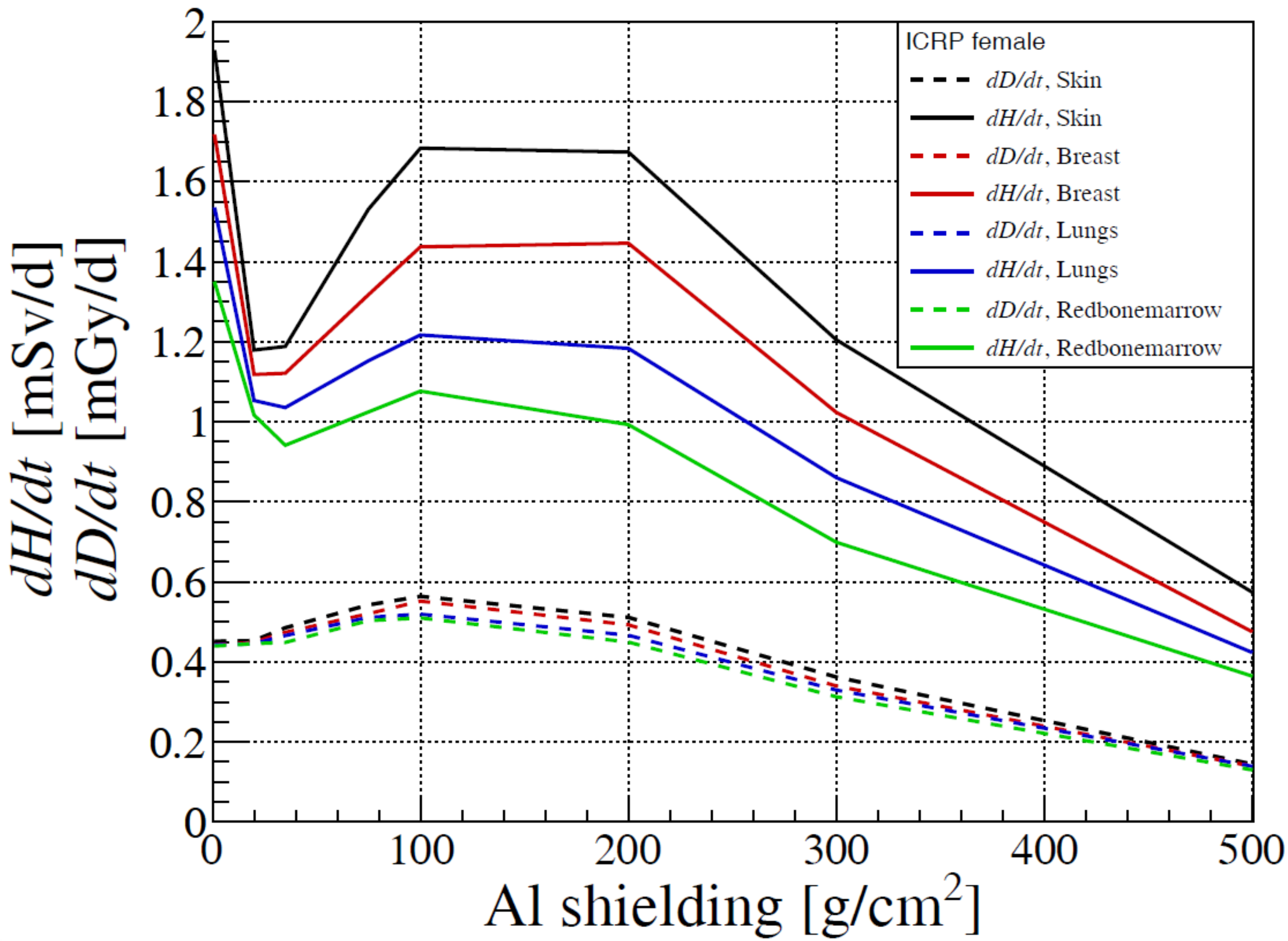
(Zeitlin, et al., SCIENCE, 2013)

BON11 & HZETRN Model from Cucinotta (NASA Tech Brief, 2011)

Absorbed Doses to the Organs using a Phantom in a similar shielded environment as MSL



Organ Dose Equivalent versus Al-Shielding female



Surface data and Calculations

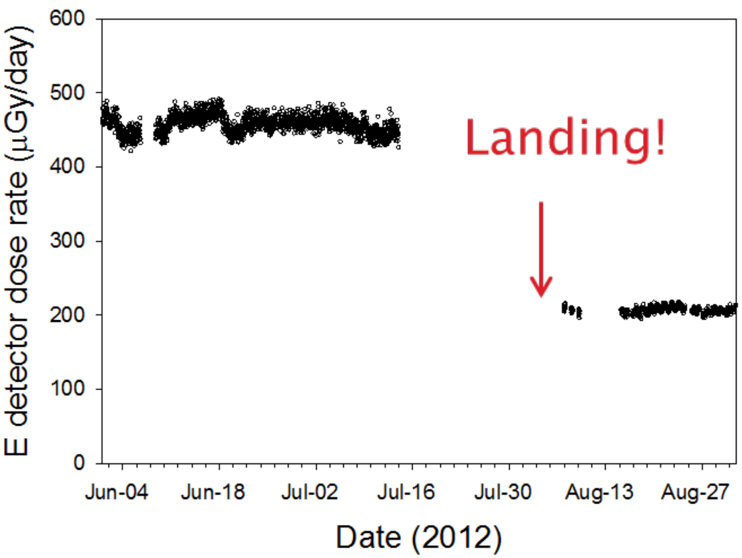
Navigation camera image showing the surface scour marks and rocks on the rover's deck…and RAD!

The Curiosity rover successfully landed in Gale crater on August 6, 2012. Situated on board the rover, RAD is the first-ever instrument to measure the Martian surface radiation environment.

NASA/JPL-Caltech

Sol 1…First RAD Observations on the Surface of Mars!

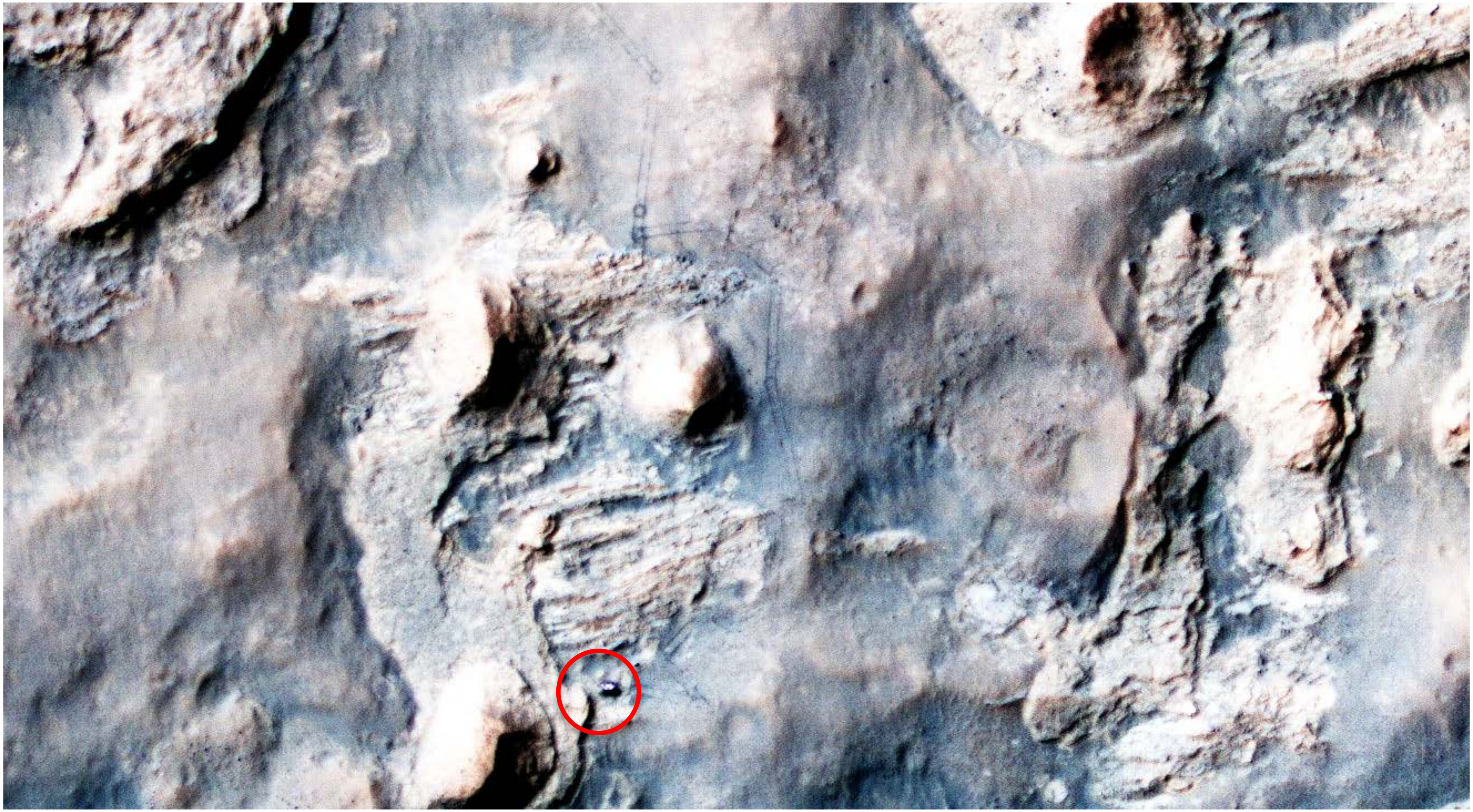
100 Years after the Discovery of Cosmic Rays on Earth…August 7, 1912…



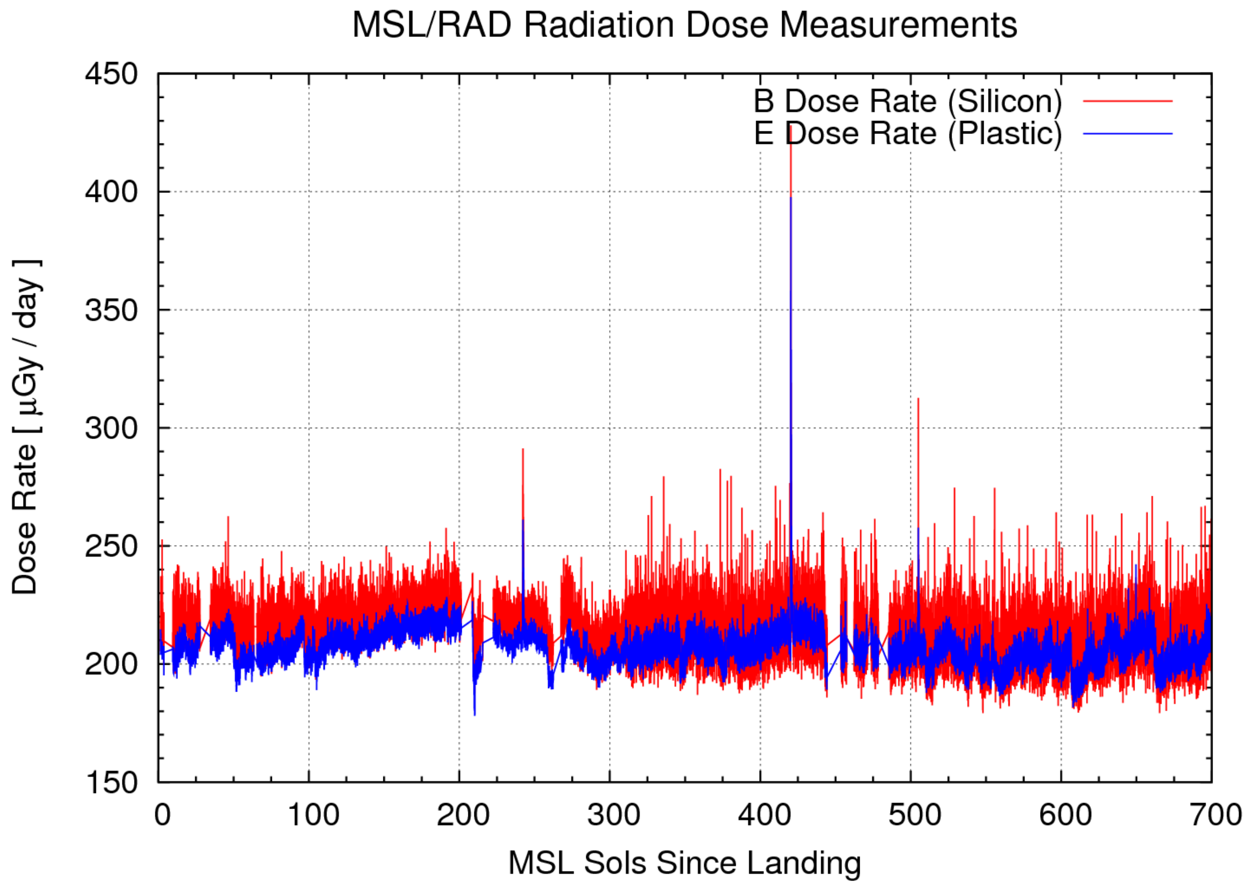
Exactly 100 years after Victor Hess discovered Cosmic Rays from his balloon in Eastern Germany…

…RAD makes the first observations of the radiation environment on the surface of another planet!

Rover Path As Seen From Orbit

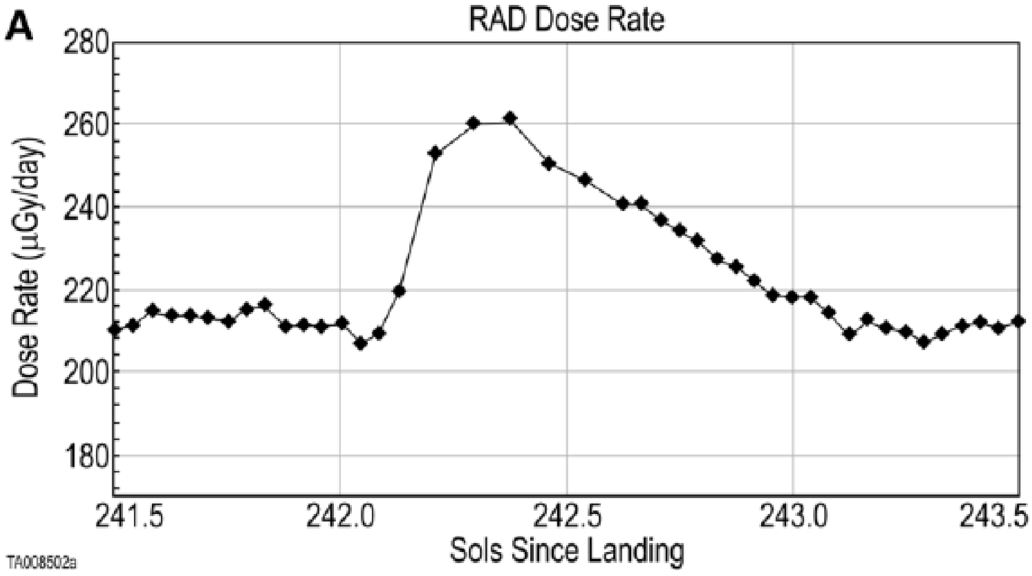


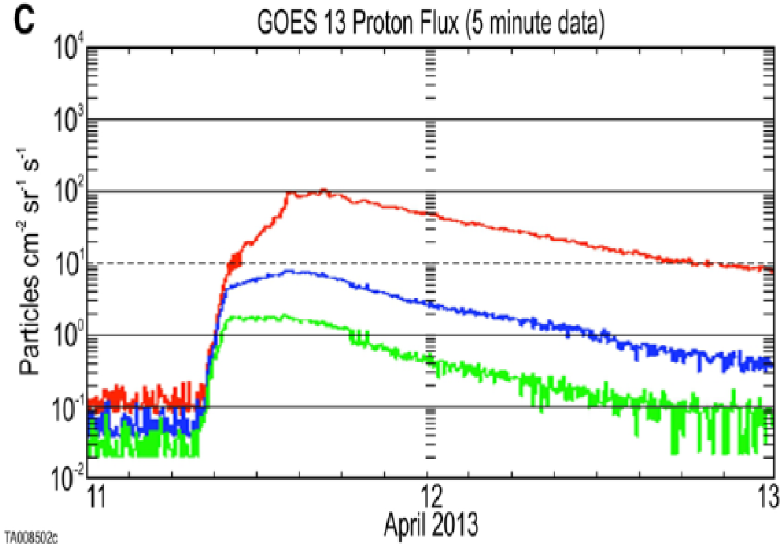
RAD Dose Rate Measurements on the Surface of Mars



RAD has now been measuring the surface radiation for more than one Mars year (> 2 Earth years). So far, only 3 SEP events have been directly observed (as well as several Forbush decreases)!

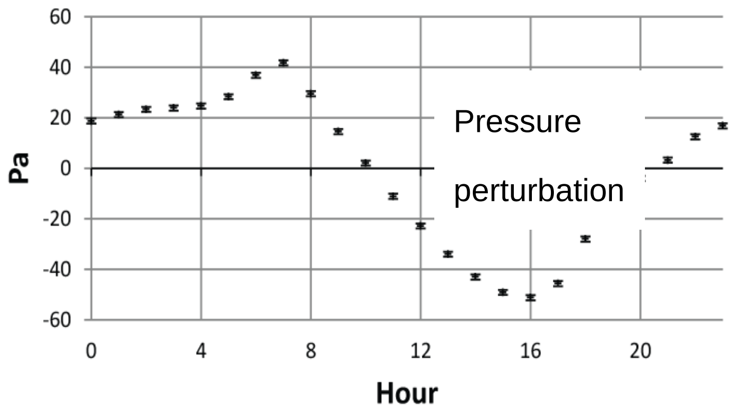
Dose rate enhancement observed by RAD on the Mars surface from the solar particle event from 11-12 April 2013 (left); same SPE event seen by GOES (right)

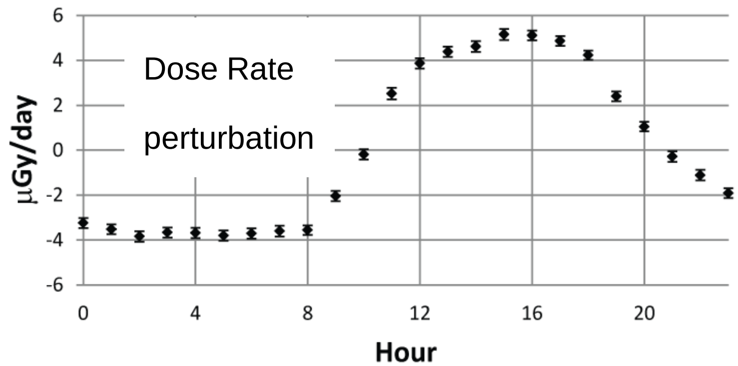


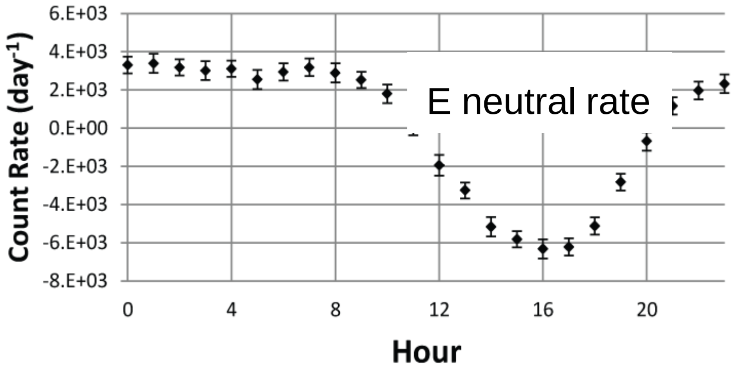


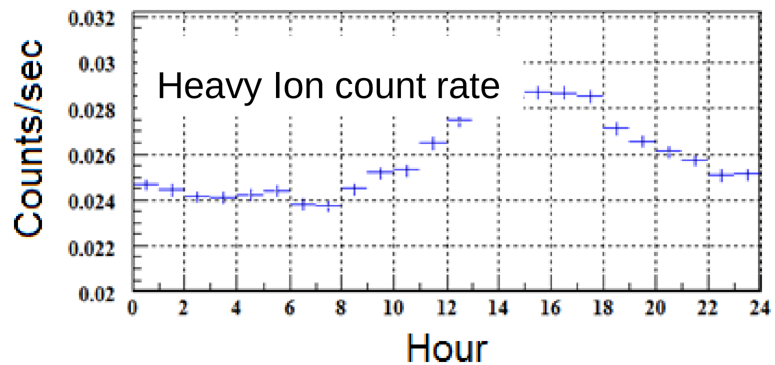
Diurnal Variations

Rafkin et al., JGR Planets 119 (3), 2014



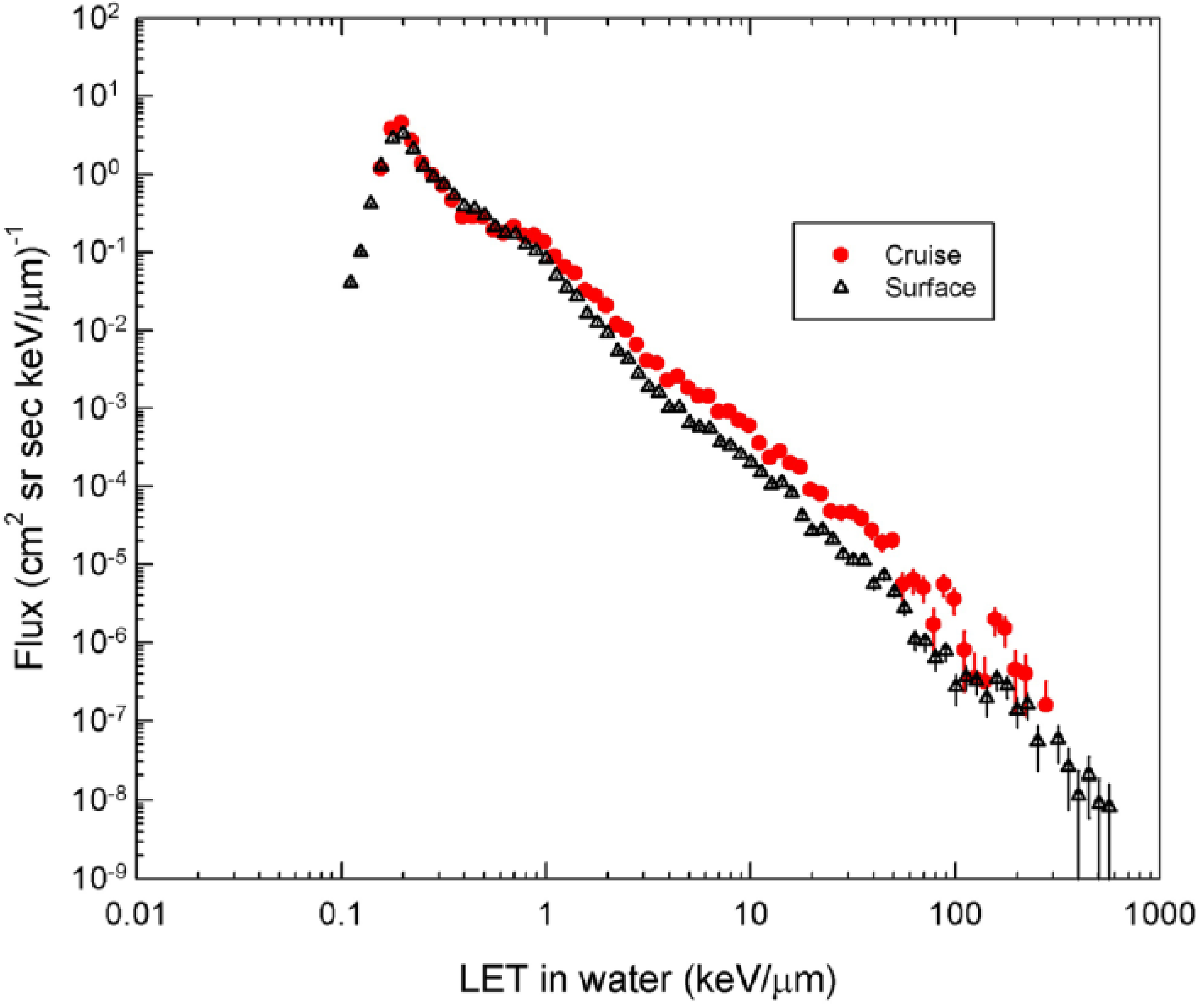




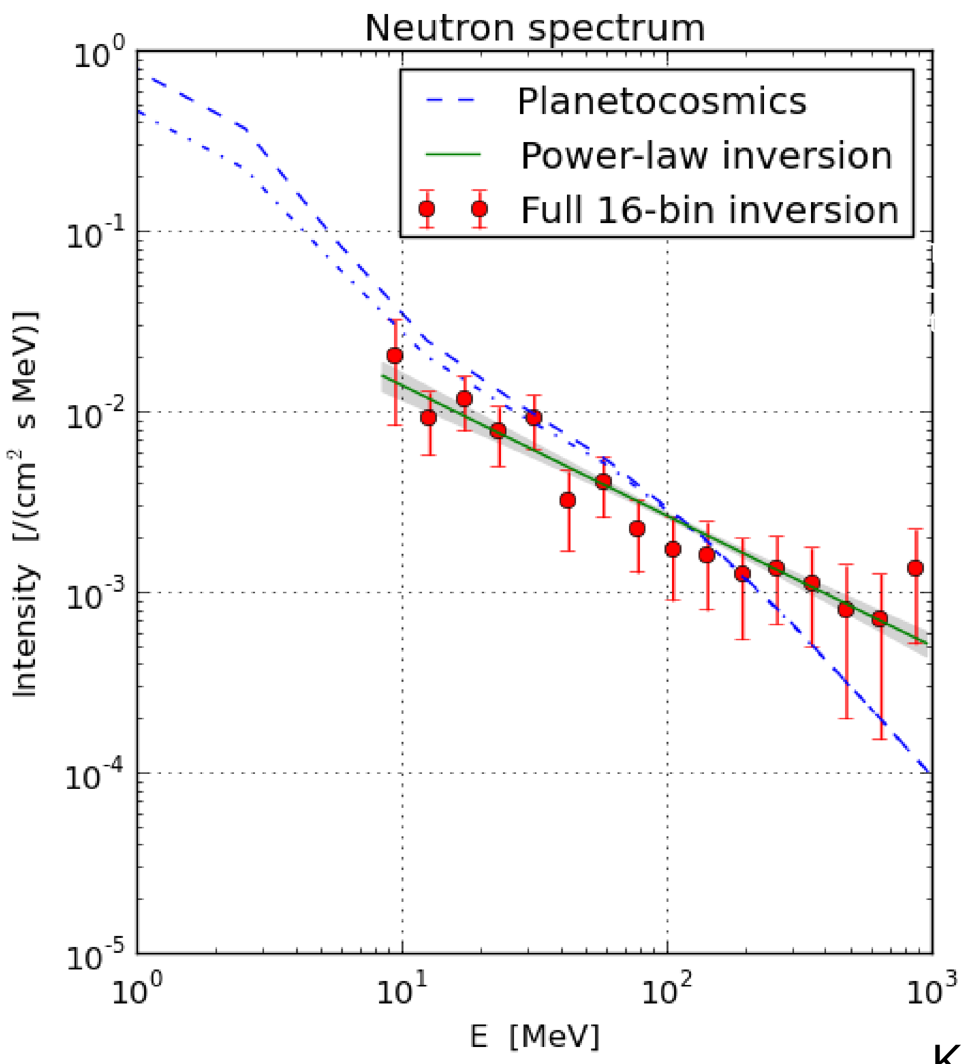


- "Thermal tide" → +- 5% daily variations in pressure → +- 2% variation in radiation dose rate, inversely correlated with P.
- Thinner atmosphere → fewer neutrons made + more heavy ions survive traversal → higher dose rate.
- Pressure data from the REMS team.

RAD Measured LET Spectra during Cruise and on Mars Surface



Neutron Particle Fluxes



D, E spectra inverted □g and neutron spectra.

Neutron threshold energy ~ 8 MeV.

D = 14 ± 4 μGy/day, about 7% of total.

H = 61 ± 15 μSv/day, about 9% of total.

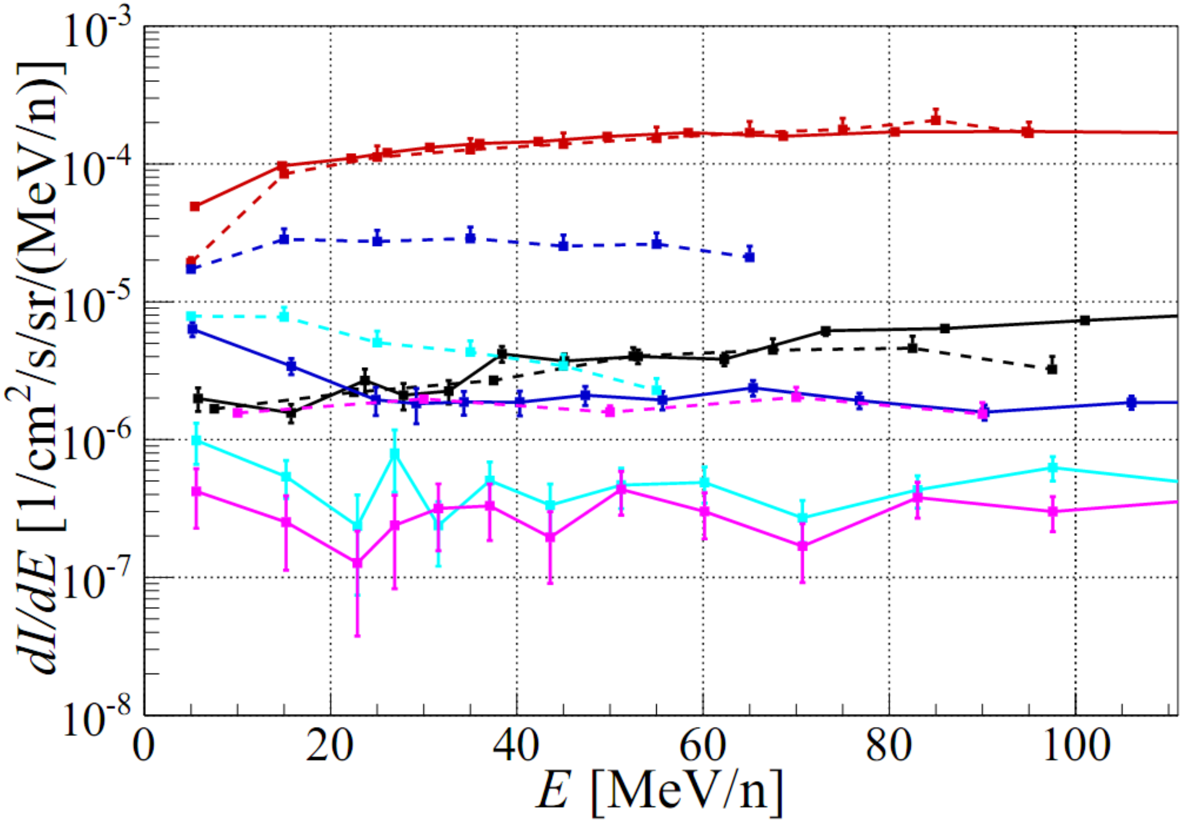
Koehler et al., JGR Planets 119 (3), 2014

MSL-Ground

- PLANETOCOSMICS GEANT4.9.6.p02
- ground at 20 g/cm^2
- primary GCR:
  - Z=1-26
  - 10 MeV/n ≤ E ≤ 1 TeV/n
  - average between Aug. 2012 and Aug 2013
- only atmosphere and ground, no rover, no detector

→ secondary particle fluxes
  - upward/downward
  - total
  - θ ≤ 30°

MSL-ground, low Z - 20 g/cm^2
(no shielding from Rover included)



solid lines: GEANT4

dashed lines:

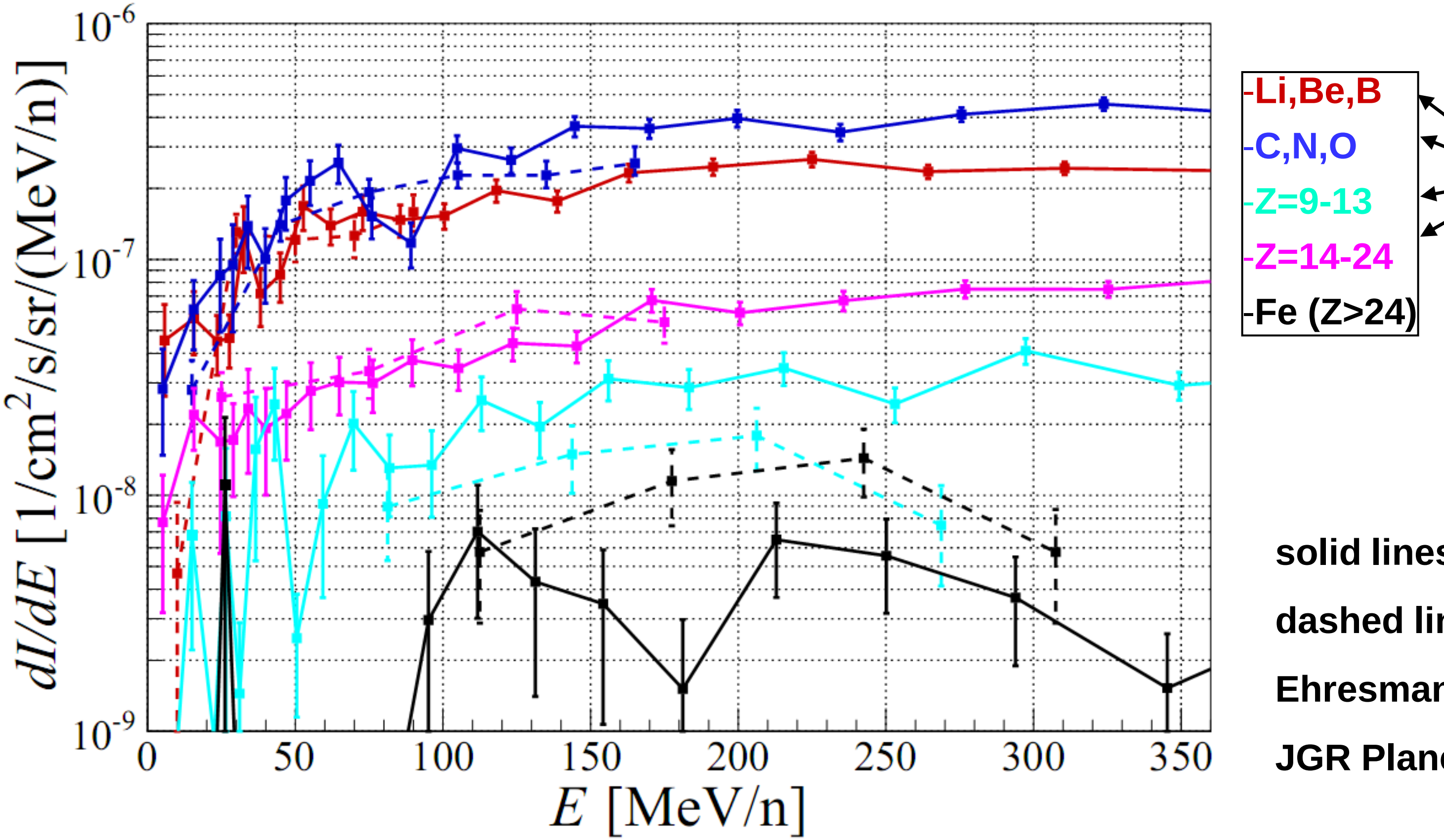
Ehresmann et al., JGR Planets119, 2014

- H, He: good agreement
- ^{2}H, ^{3}H, ^{3}He:

simulations ≈ factor 10 lower than measurements

MSL-ground, high *Z*- 20 g/cm²

(no shielding from Rover included)



GEANT4
(all isotopes)

GEANT4
(only ^{56}Fe)

solid lines: GEANT4

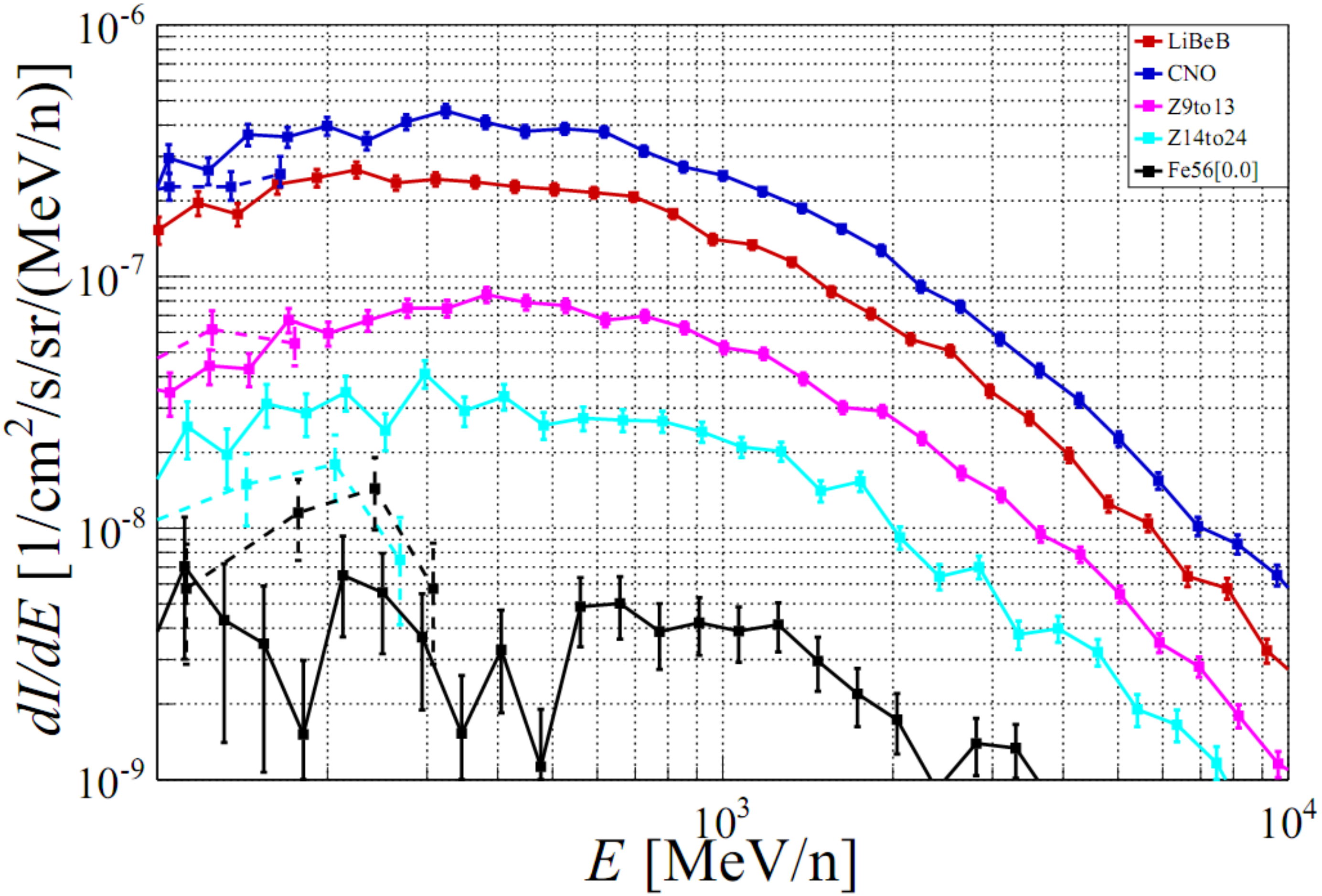
dashed lines:

Ehresmann et al.,

JGR Planets 119, 2014

MSL-ground, high *Z*, different scale - 20 g/cm^2

(no shielding from Rover included)

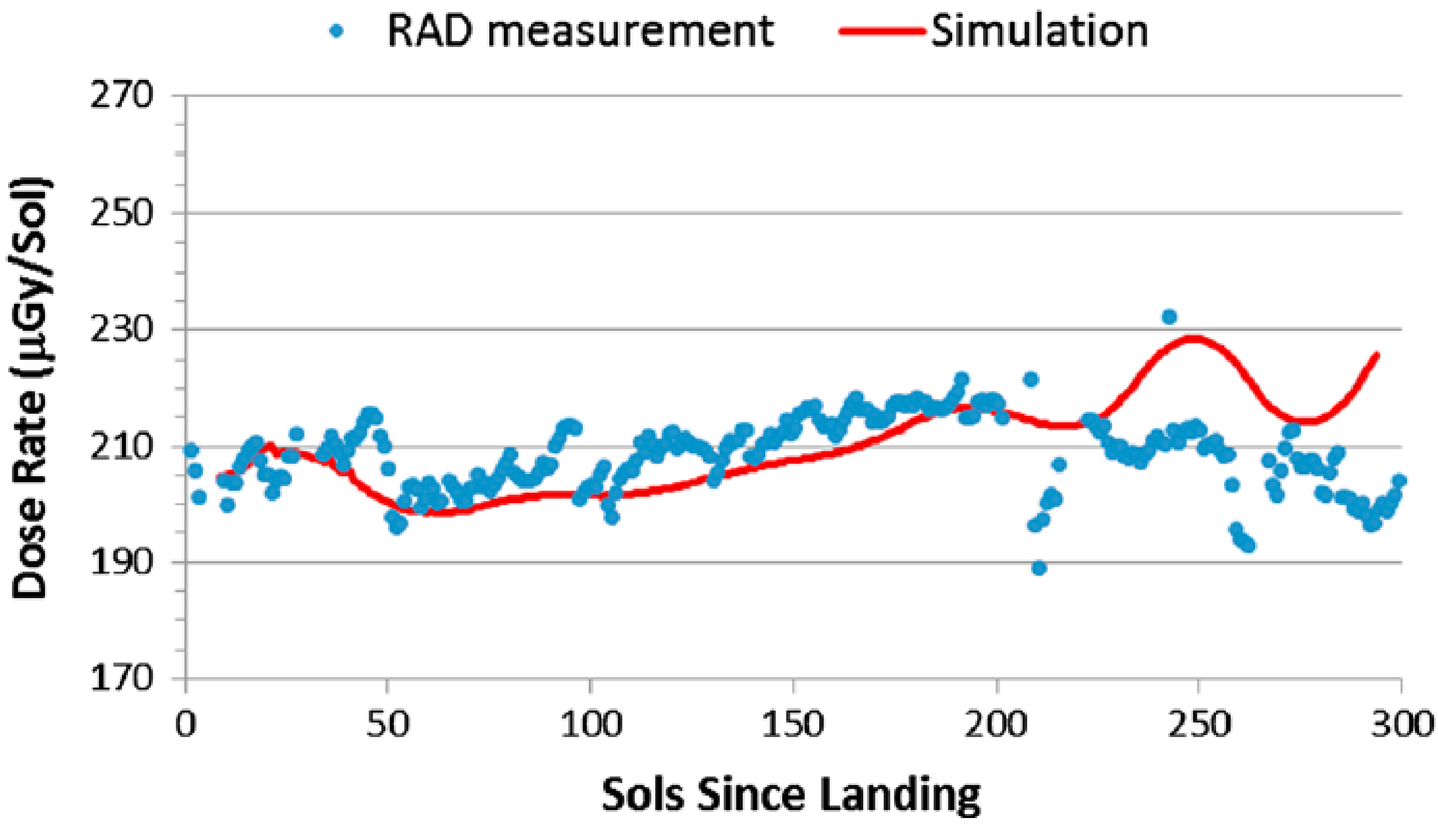


solid lines: GEANT4

dashed lines: *Ehresmann et al., JGR119, 2014*

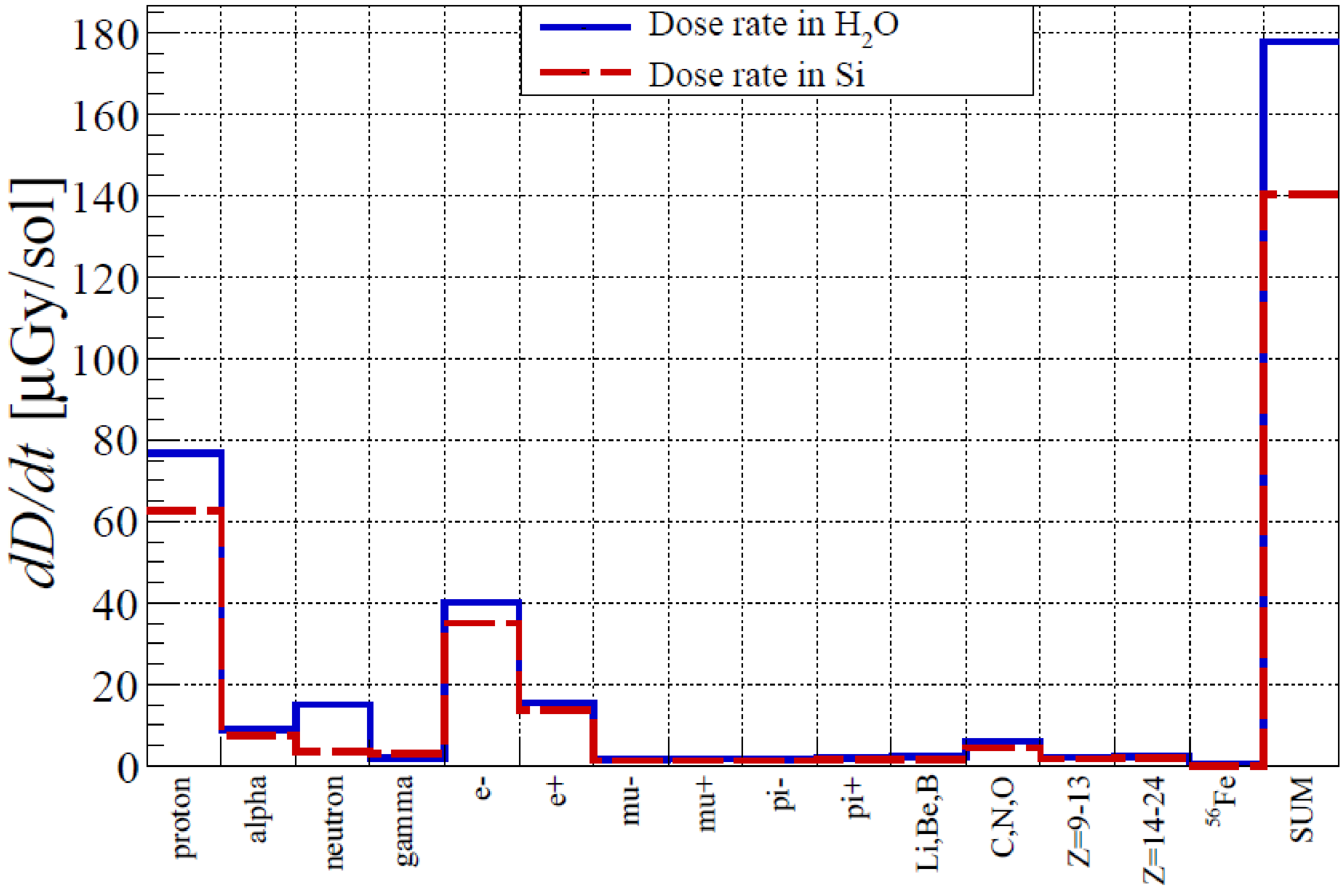
DLR

Badhwar O'Neil 2011/ HZETRN in comparison to RAD Measurement



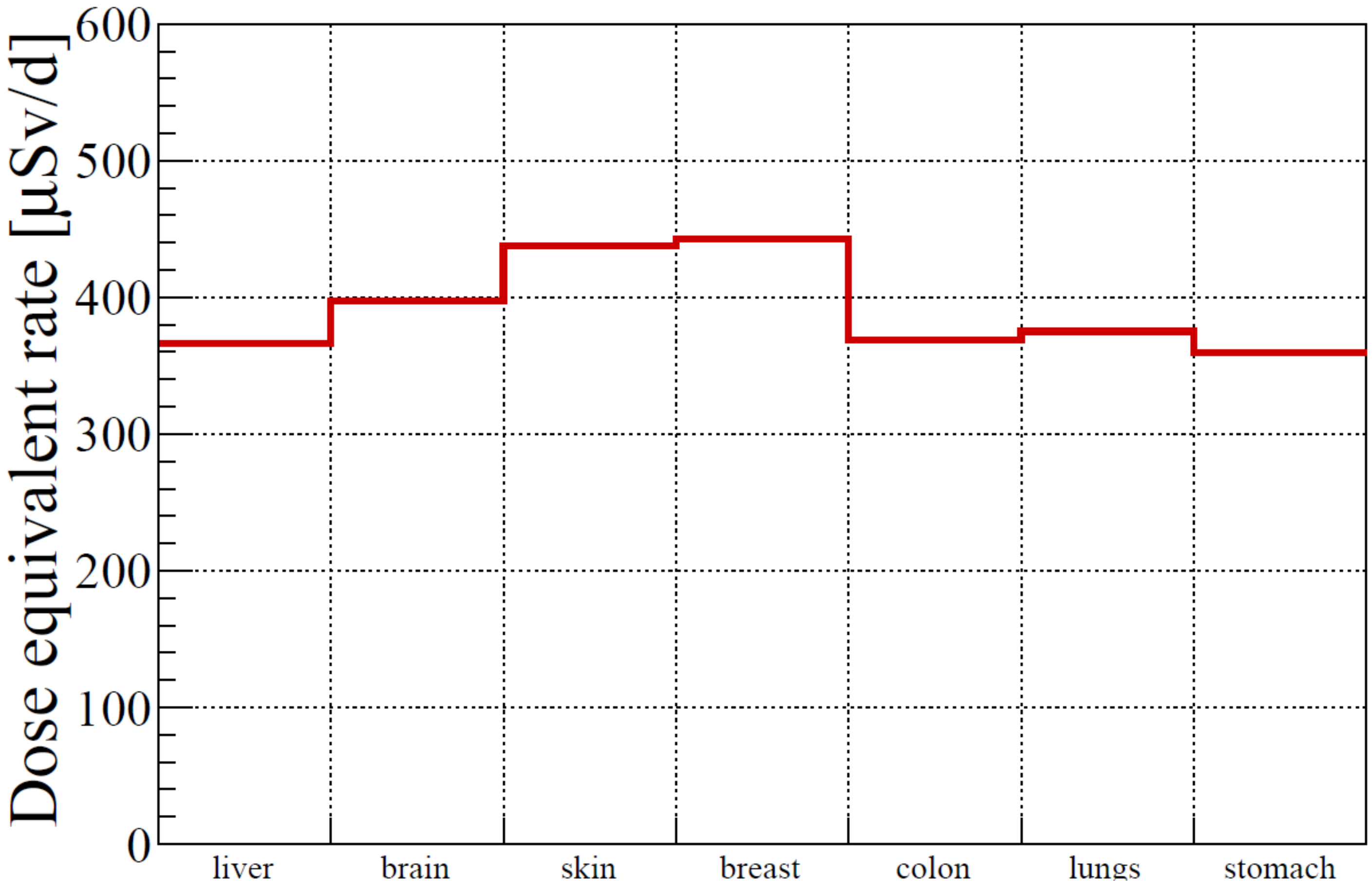
Kim et al., JGR Planets 119 (3), 2014

Absorbed Dose Rate on the Surface of Mars
DLR Model/Geant4



Mars Surface measurement about 205 µG/day

Organ Dose on the surface of Mars under EVA condition



MSL-RAD: 0.20±0.04 mGy/d; 0.64±0.12 mSv/d, Q=3.1±0.3

Radiation Environment Measured by MSL/RAD (2012-13) (GCR only)

RAD Measurement	Mars Surface	Cruise	Units
Charged Particle Flux	0.26	0.64	particles cm^{-2} s^{-1} sr^{-1}
Fluence (A2*B)	1.65	3.98	cm^{-2} s^{-1}
Dose Rate	0.205 +/- 0.05	0.464 +/- 0.057	mGy/day
Avg. Quality Factor <Q>	3.2 +/- 0.3	3.82 +/- 0.3	(dimensionless)
Dose Equivalent Rate	**0.7 +/- 0.17**	**1.84 +/-0.30**	**mSv/day**

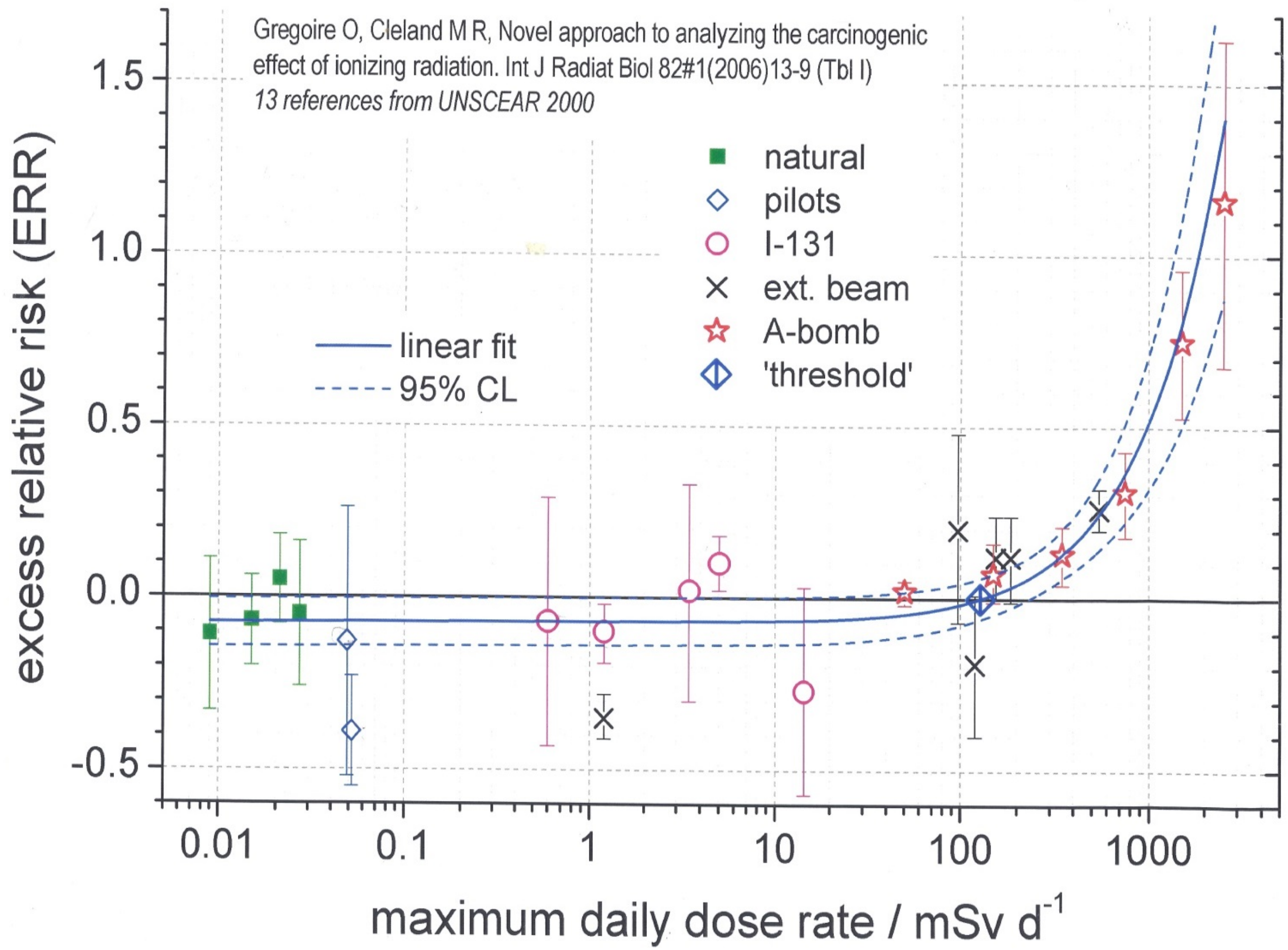
Hassler et.al, Science 2013

Preliminary Dose Estimates for NASA "Design Reference" Mission

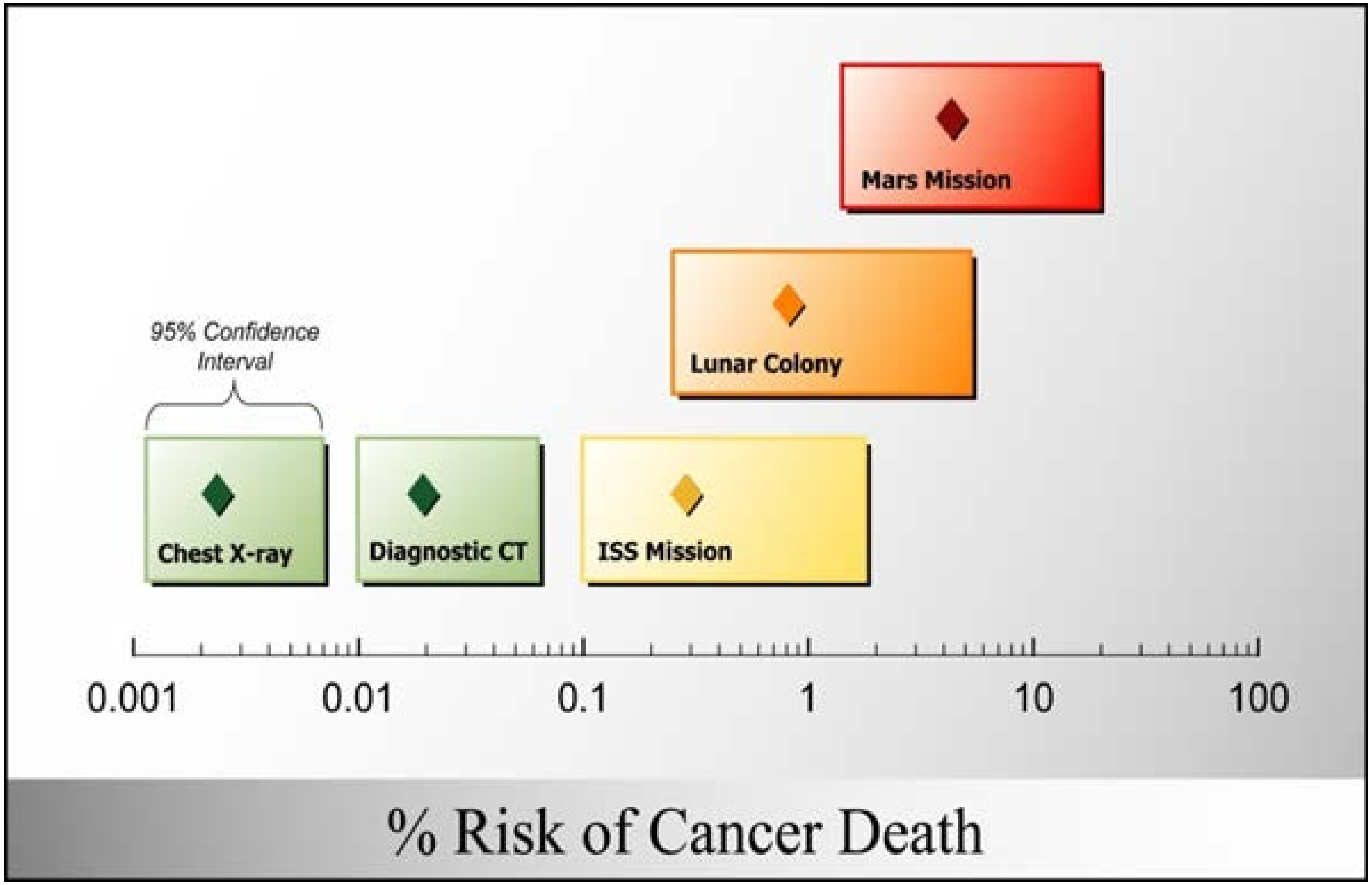
Mission Phase	Dose Equivalent	Notes
Astronaut Career Limit*	**~0.4-1.5 Sv**	depends on age, gender, etc.
Cruise to Mars (180 days)	~340 mSv	near SolarMax
Mars Surface Mission (600 days)	~420 mSv	Thin habitat shielding
Mars Surface Mission (300 days)	~210 mSv	Thin habitat shielding
Return to Earth (180 days)	~340 mSv	near SolarMax
Total Mission Dose Equivalent (300 days on Mars)	**~0.9 Sv**	300 days
Total Mission Dose Equivalent (600 days on Mars)	**~1.1 Sv**	600 days

*Astronaut Career Limits vary by Space Agency. NASA Astronaut Career Limits are based on 3% excess career fatal cancer risk, and vary by age, gender, etc.

Excess Relative Risk as function of dose rate



Current estimates of cancer risks and 95% confidence bands for adults of age 40-yr, the typical age of astronauts



Durante & Cucinotta, Nature Rev. Cancer (2008).

Summary

- RAD make the first measurements on the transit to Mars and on the surface of Mars
- RAD obtained a rich data set during cruise and on surface; surface operations were performed continuously…but still providing a snap shoot
- To fully analyze & understand the Surface data…takes time to accumulate statistics of high LET particles - as statistic improves spectral measurements will come more into focus
- Only 3 (relatively) weak SEP events detected so far → need larger sample size to understand potential hazards
- Simulation of data: Good results after updating the GCR input spectra for dose and dose equivalent , but sometimes high discrepancies in fluxes
- Total Dose Equivalent in the NASA Design Mission between 0.9 Sv and 1.1 Sv

RAD - Next Steps

- Measuring throughout the solar cycle important for full understanding of radiation environment → Radiation environment is highly variable on short- and long-term time scales
- Neutron and particle Spectra vs Time
- Looking forward to SEP Events (declining phase of this Max)
- Separation of concurrent influences of solar modulation and seasonal pressure cycle
- Heliospheric Variability & Test of Modulation Parameter
- Improvement & Validation of Transport Models (both GCR & Atmospheric)
- RAD Measurements incorporated into Heliospheric Constellation of Radiation & Energetic Particle Measurements
- Cooperation with other MSL instrument teams (e.g., REMS, DAN, SAM) ongoing complement research

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RAD's new Home: Mastcam-100 image of Mount Sharp's layers, Canyons and Buttes

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