Radiation Measurements during the Cruise to and on the Surface of Mars with MSL/RAD

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Introduction

The Radiation Assessment Detector (RAD) on board the Mars Science Laboratory's *Curiosity* rover is a highly capable instrument designed to measure the radiation environment encountered at the surface of Mars.

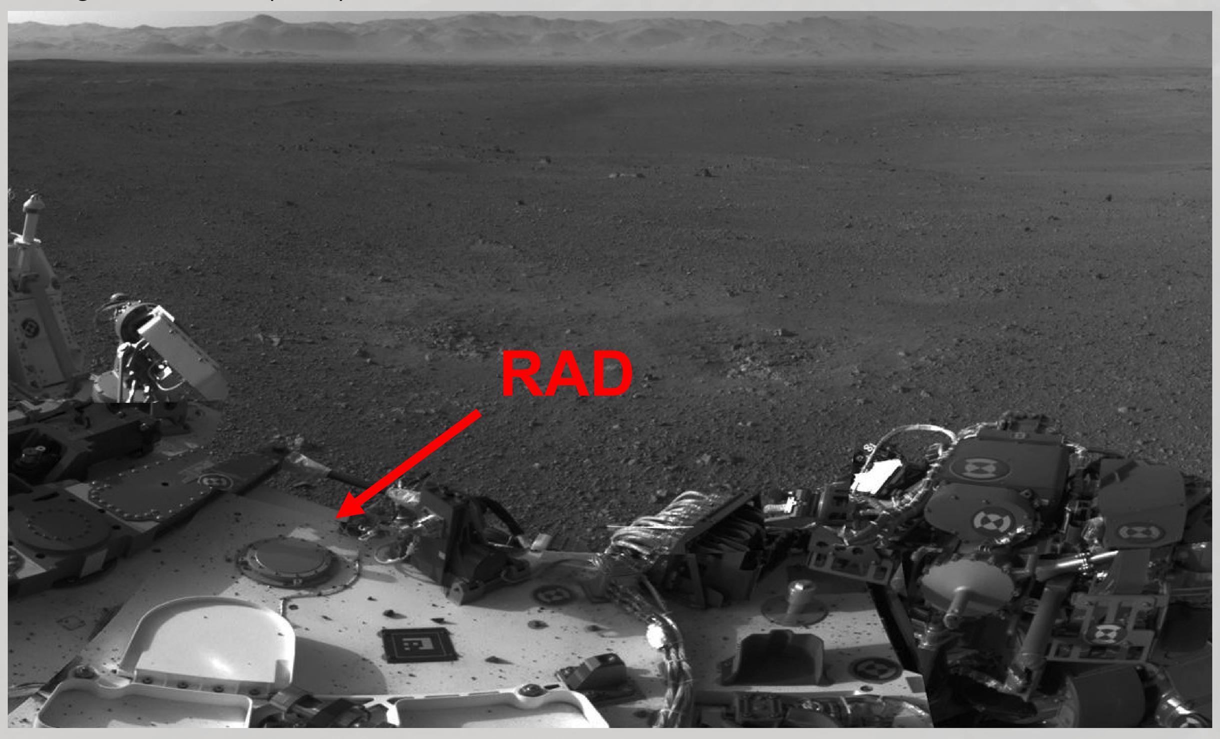
This surface radiation environment is to a large part induced by the incoming Galactic Cosmic Rays (GCRs) that create a diverse particle field on the surface by interacting with the atoms of the Martian atmosphere and the soil of Gale crater.

Understanding this radiation is of great importance for planning potential future manned mission to Mars, as radiation can prove to be hazardous for human life and has to be well analyzed to assess the risks it poses.

Since the successful landing in Gale crater on 08/06/2012, RAD has been conducting its measurements of the surface radiation environment almost continuously with varying measurement cycles of 32 minutes (first ~300 sols), 60 minutes (during solar conjunction), and 16 minutes (from sol ~300 and ongoing).

In addition to these surface measurements, RAD was also already operating for large parts of the 253-day cruise to Mars. Combined, these measurements give unique insight into the expected radiation exposure for a potential manned mission to Mars.

Here, we give a brief overview of the RAD sensor head and its measurement capabilities. Furthermore, we present dose rate measurements of the radiation environment during the cruise phase and on the surface of Mars, and during the Solar Energetic Particle (SEP) events detected so far.



Cruise Phase

RAD was already taking measurements for large parts of the cruise phase to Mars to serve as a proxy for the expected radiation exposure inside a spacecraft for potential future manned mission.

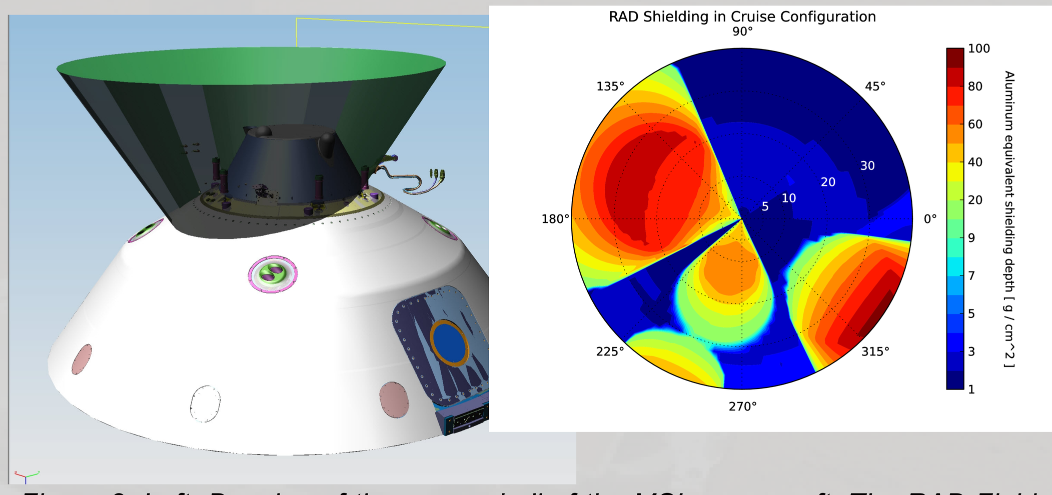


Figure 2: Left: Drawing of the upper shell of the MSL spacecraft. The RAD Field-Of-View (FOV) is indicated by the green cone. Right: Shielding depth in the in the upward RAD FOV. Zenith angle corresponds to radius of the circle (indicated by the white numbers). While most of the FOV was more or less free of shielding material (blue-shaded), there were some heavily shielded areas (hydrazine tanks, parachute) with depths up to ~100 g/cm².

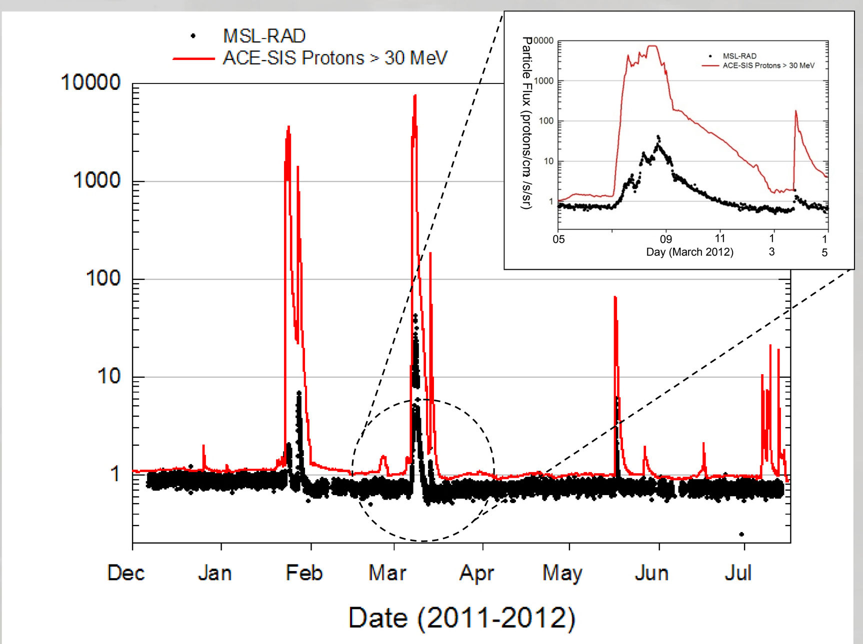


Figure 3: Comparison of RAD and ACE-SIS proton counts during the March 2012 SEP events (events 3 and 4 in Fig. 4).

RAD particle fluxes during SEP events can be compared to data from other spacecraft that saw the same event → insight on particle propagation in the heliosphere.

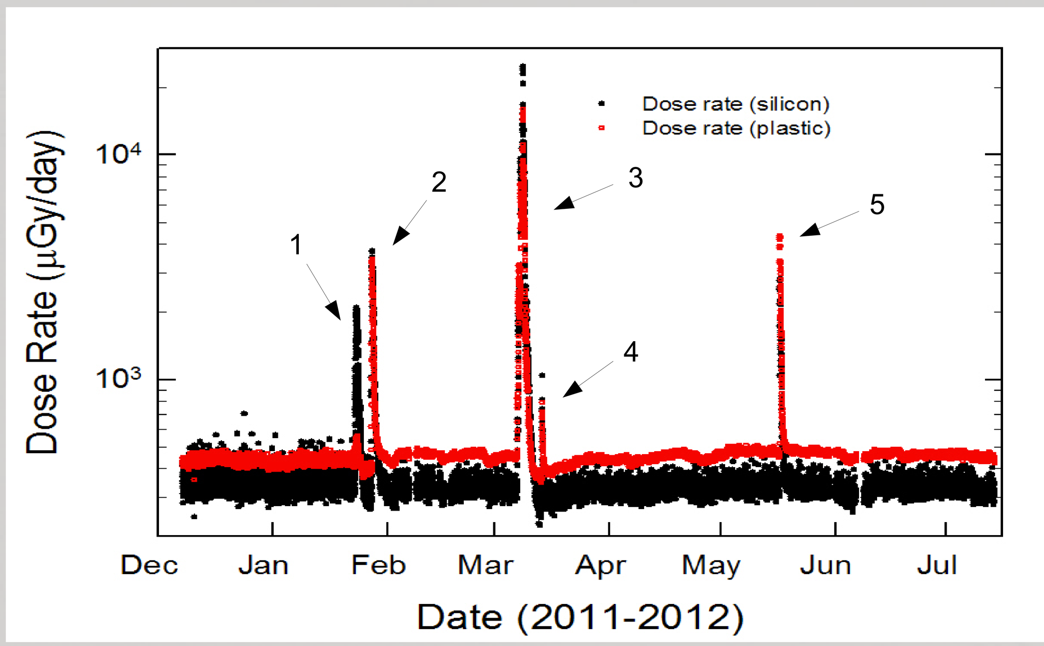


Figure 4: Absorbed dose rate measurements during the cruise phase conducted with the B (black) and E detector (red). During cruise RAD observed 5 SEP events (indicated by the arrows). Note that these are not free space measurements, but rather inside the spacecraft behind shielding (see figure 2).

During the cruise phase, RAD measured an average absorbed dose rate of ***~480 µGy/day*** (during solar quiet times).

The main contribution to the encountered radiation environment stems from GCRs. Besides this constant contribution, RAD also detected 5 Solar Energetic Particle (SEP) events with short-term increases of the dose rate by 1 to 2 orders of magnitude during the 253-day cruise phase.

In terms of dose equivalent, these ***5 SEP events*** contributed ***~5 %*** to the total dose encountered during cruise.

SEP events are highly variable in occurrence rate and intensities → larger events could contribute significantly more to the total dose (> order of magnitude).

RAD cruise measurements*:

- Absorbed dose rate: ~480 µGy/day
- Quality factor: ~3.8
- Dose equivalent rate: ~1.84 mSv/day

****Zeitlin, et al., Science (340), 2013.***

Dose equivalents measured during SEP events*:

23-29 Jan: 4.0 mSv

7-15 Mar: 19.5 mSv

17-18 May: 1.2 mSv

Total SEP: 24.7 mSv

Total dose cruise: 465 mSv

The RAD Sensor Head

RAD is a combined *Charged* and *Neutral Particle* analyzer comprised of a solid state detector telescope and separate scintillators with active anti-coincidence logic.

- Mass = 1.56 kg
- Power = 4.2 W
- Volume = 10.3 x 12.2 x 20.4 cm3
- Field-Of-View = 65 deg. (view cone)
- Geometric Factor = 1 cm2 sr

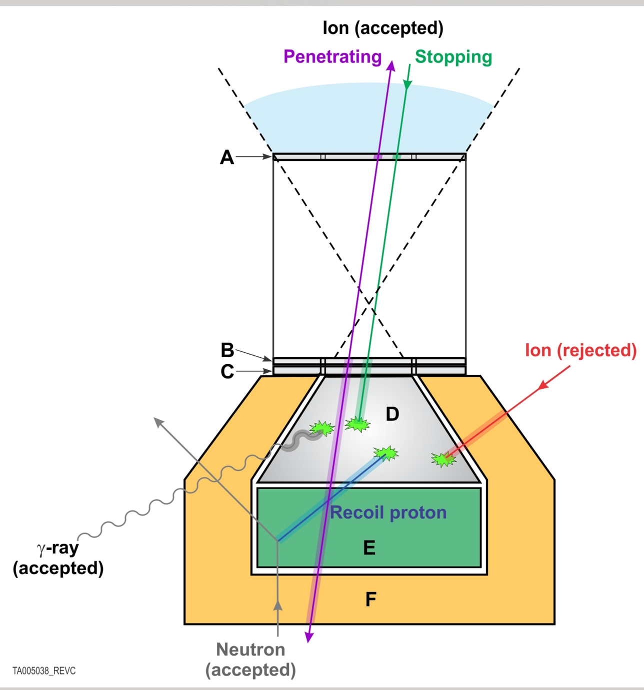


Figure 1: Schematic of the RAD sensor head

The RAD sensor head consist of:

- 3 Si detectors (**A** – **C**)
- CsI scintillator (**D**)
- Plastic scintillator (**E**)
- Second plastic scintillator (**F**) acting as anti-coincidence

Absorbed dose is recorded in detectors **B** (Si) and **E** (tissue-equivalent).

Linear Energy Transfer (***LET***) spectra in Si are recorded in **B** in coincidence with **A** (range: 0.3 – 1000 keV/µm).

LET-based ***quality factors*** → convert absorbed dose into ***dose equivalent***.

Neutral Particle Detection:

- Particles are detected in **D** and **E** (**C** and **F** used as anticoincidence)
- Differences in detector response functions of **D** and **E** allow separation into ***neutrons*** and ***γ-rays***
- **D** is a high-Z material → effective for γ-ray detection
- **E** has a high proton content → high cross section for neutron interactions
- ***Inversion method*** allows reconstruction of initial neutron and γ-ray spectra (~10 to several hundred MeV)
- See talk by ***Dr. Jan Koehler*** for more information (***Tuesday - 11.30 h***).

Charged Particle Detection:

- Particles have to pass through the telescope AB (A segmented in inner and annular outer part)
- Stopping particles come to rest in detectors **B** through **E** and their total energy is known → differential energy spectra (up to several hundred MeV/nuc depending on ion species)
- Penetrating particles deposit energy in detectors **A** through **F** (bottom part) → integral spectra
- Particles distinguishable into different ion species and isotopes (1 ≤ Z ≤ 26)

Radiation Measurements on the Martian Surface

Since the landing in Gale crater on Aug 6 2012, RAD is the first-ever instrument to measure the radiation environment on the surface of Mars.

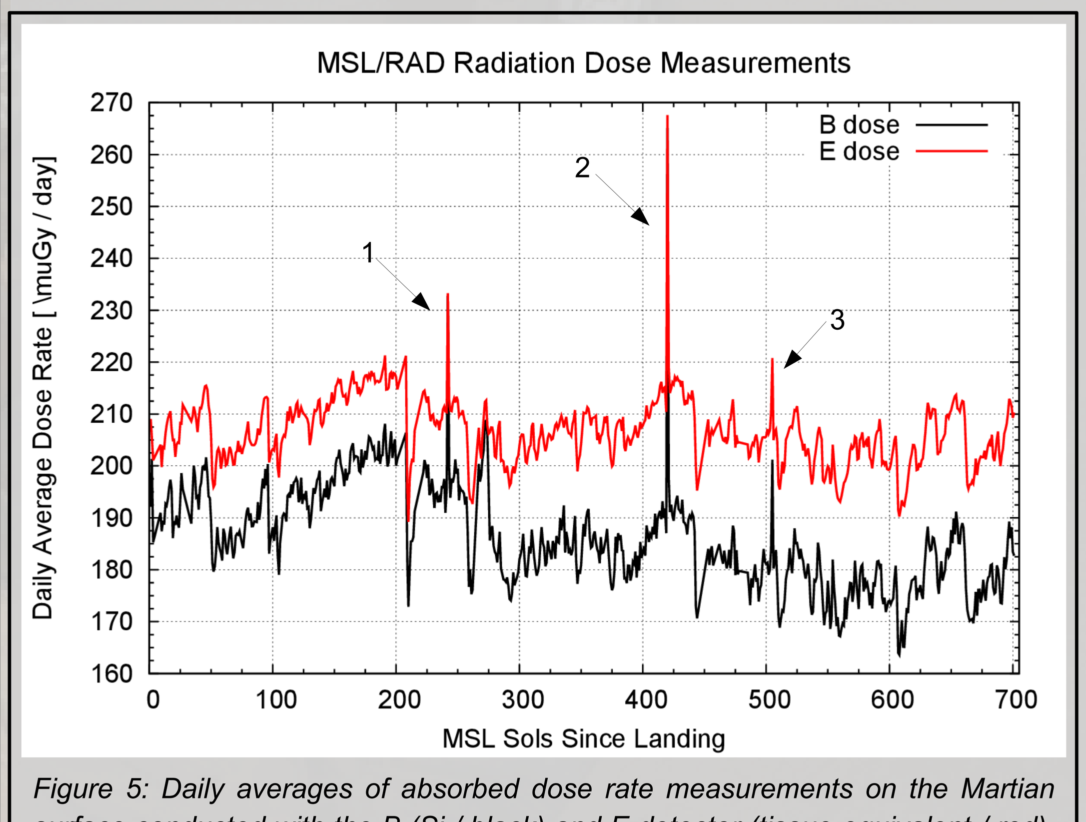


Figure 5: Daily averages of absorbed dose rate measurements on the Martian surface conducted with the B (Si / black) and E detector (tissue-equivalent / red). The 3 SEP events observed by RAD so far are marked by the arrows and numbers. The B dose is corrected for contributions from the rover RTG and converted to dose into water.

The ***absorbed dose rate*** on the surface is lower (~***210 µGy/day***) compared to the one encountered during cruise (~480 µGy/day). A large part of the difference is explained by the fact that the planet provides shielding from incoming radiation from the hemisphere below RAD.

The average ***quality factor*** is also lower on the surface, ***3.05*** compared to 3.8 in cruise → this is mainly due to the average shielding on Mars being higher than in the cruise phase. Applying the average quality factor to the absorbed dose yields an average ***surface dose equivalent rate*** of ***~0.64 mSv/day*** (cruise: 1.84 mSv/day).

The radiation environment is susceptible to changes both on long- and short-term bases: solar modulation of the incoming GCR flux, seasonal pressure cycle on Mars (long-term); diurnal pressure variations and heliospheric rotation (short-term)

The 3 SEP events observed so far have been comparably weak, with the most intense one (event 2 on sol 420) leading to a short-term increase of the radiation dose of a factor of 2 (in single observations).

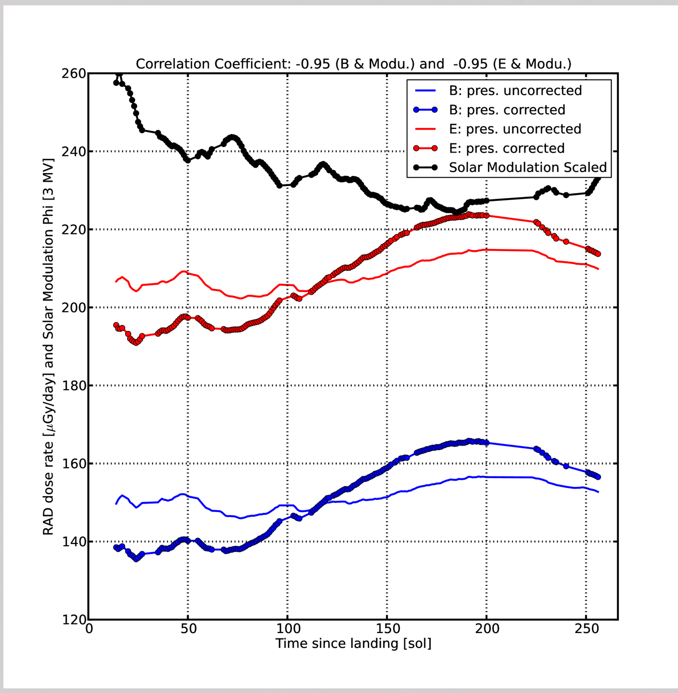


Figure 6: Pressure-corrected RAD dose rate profiles (B: blue / E: red) for the first 260 Sols, overlain with the solar modulation parameter (black). A proposed anti-correlation between solar modulation and dose can be seen. This plot shows preliminary analysis from Dr. Jingnan Guo.

Solar modulation and atmospheric column mass both can influence the surface radiation field → sometimes in opposite directions.

A higher solar modulation leads to attenuation of the incoming GCR flux (and vice versa). Higher atmospheric column mass also leads to a decrease in the primary GCR flux, but also increases the cross section for secondary particle interactions (and vice versa).

It is important to disentangle these concurrent factors → e.g., pressure-corrected dose rate profile.

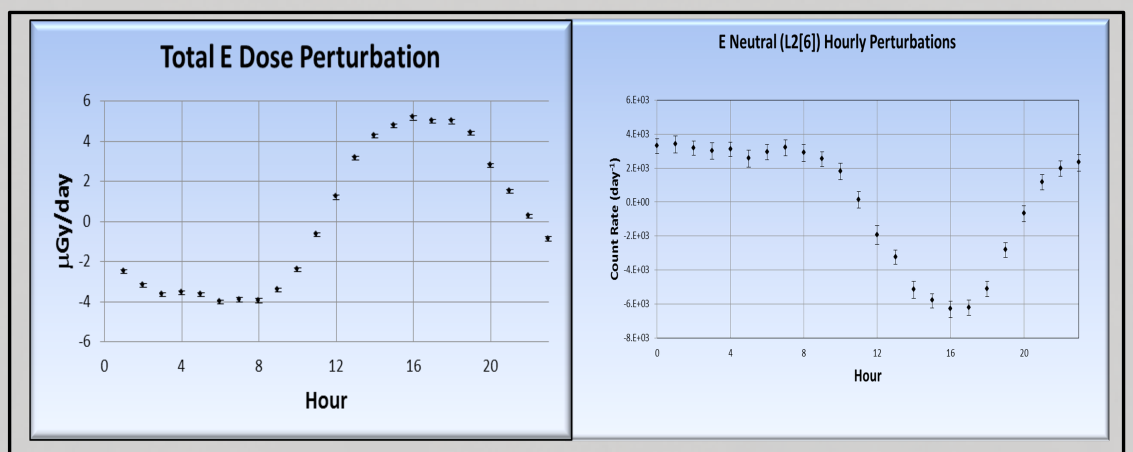


Figure 7: Left: Mean perturbation of the E dose over the course of one sol. Right: Mean perturbation of the E neutral particle counter over the course of one sol. While the dose perturbation is anti-correlated to the daily pressure trend, the neutral counter is correlated.

RAD sees a ***diurnal variation*** in the dose rate caused by recurring pressure changes due to the thermal tide; the dose rate changes are anti-correlated to the pressure variations (higher pressure → lower primary GCR flux). However, secondary neutral particles show a correlation with pressure (higher pressure → higher secondary production rate). See ***Rafkin, et. al., JGR Planets 119 (3), 2014*** for more details.

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