Radiation Measurements of the Mars Science Lab Radiation Assessment Detector (MSL-RAD) on the Surface of Mars

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The Radiation Assessment Detector (RAD) was designed to characterize the radiation environment as "Life Limiting Factor" to habitability and to help to prepare for future human exploration of Mars. The Mars Science Laboratory spacecraft (MSL), containing the Curiosity rover, in which RAD is integrated, was launched to Mars on November 26, 2011. Although not part of the mission planning, RAD was operated already during the 253 day and 560 million km cruise to Mars and made the first detailed and time-resolved

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measurements of a radiation environment that will exist inside future spacecraft carrying humans to Mars and in other deep space missions. On August 6, 2012 the Curiosity rover landed on the surface of Mars. RAD started measuring the surface radiation exactly 100 years after the discovery of cosmic rays on August 7, 1912 RAD made the first observation of the radiation environment on the surface of another planet and is still gathering/recording data today. Here we present data on particle fluxes, absorbed dose and dose equivalent from both galactic cosmic rays and solar particles together with model calculations. The dose equivalent rate is found to be 0.64±0.12 mSv/day on the surface on Mars from Aug 7, 2012 until June 1, 2013 and 1.84±0.3 mSv/day during cruise. The high level of complexity of the data allows for benchmarking of space radiation transport models and thereby supports the validation and improvement of predictive models for health risks of astronauts during space missions.

I. Introduction

FOR decades space agencies have been planning a human mission to Mars being aware of risks to the systems and to the astronauts. A lot of roadmaps exist describing the steps which have to be done by prioritizing the science topics to optimize the preparation and performance of such a mission. One major risk is posed by the radiation environment in the solar system. The exposures by this environment can be described by two exposure scenarios. One is an exposure to the galactic cosmic ray (GCR) component with very low fluence (smaller than 4 particles $cm^2 s^{-1}$) and comparably low average exposure rates to the astronauts, the second is a potential high exposure to solar protons from solar flares and coronal mass ejections. GCR consist mainly of protons and heavier ions with very high energies up to 10^{11} GeV resulting in a high penetration depth in matter. Highest fluxes are observed at minimum solar activity and vice versa due to the shielding of the heliospheric magnetic fields.[1] With increasing depth in matter the production of secondary radiation increases. After a first decrease in exposure due to absorption and fragmentation of biologically highly relevant high-Z primary particles in spacecraft structures made of aluminum, secondary particles cause an increase in exposure, which after several hundred g/cm^2 shield thickness declines again. In Hydrogen rich materials like Polyethylene the increase of exposure due to secondary particles does not exist. A spacecraft design using an optimized combination of Hydrogen rich materials and aluminum would result in an only modest reduction of the level of exposure. Considerable reductions of exposures would need again a shield thickness of several hundred g/cm^2, which is an unrealistic scenario considering high launch costs of shielding mass and competition with other necessary operational resources.[2] The use of in- situ material on Mars surface for the construction of habitats indeed offers the provision of appropriate shield thickness to reduce the exposure in habitats to a level as it exists on Earth.

Since there are no human data from heavy ion exposures experimental models must be applied or developed to estimate cancer, and other risks, causing large biological uncertainties limiting the ability to evaluate risks and effectiveness of mitigations. [3,4] Unique damage to bio-molecules, cells, and tissues occurs from heavy ions. They are therefore a biological challenge and cause the major problem for long term space missions, since excess risks for radiation induced cancer death become considerable and may be judged unacceptable.

The exposure to medium energy protons from solar energetic particle events can be prevented, since mass shielding measures are effective for these particle energies. Only small shelters inside spacecraft may be provided; optimized design of spacecraft and its interior are needed to limit mass. Exposures to solar protons are rare events which are however unpredictable. Event alert and responses are essential for crew safety. Warning time may be as low as 30 minutes in worst case situations. Therefore, interplanetary missions remain an operational challenge.

Estimates of exposure levels to humans for different mission scenarios were always based on environmental and transport models. [5-12] Since measurements inside a spacecraft and on the surface of Mars were absent the NRC/NAS recommended in May in its “Safe on Mars” recommendations “to measure the absorbed dose in a tissue equivalent material on Mars at a location representative of the expected landing side” in order to validate radiation transport codes, thereby insuring the accuracy of radiation dose predictions.[13] In 2004 the NASA Living with the Star Radiation workshop recommended the collection of radiation data on the surface of Mars in order to be able to project crew health risks and designing protective surface habitats. This comprises measurements of particle fluxes and energy spectra from all primary and secondary particles to calculate linear energy transfer, dose, and dose equivalent separately for each particle type during solar minimum and maximum and the atmospheric and surface variations.

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Based on these recommendations the Radiation Assessment Detector (RAD) was selected for Mars Science Laboratory (MSL) in 2004 with the objective to “Characterize Surface Radiation as Life-limiting Factor” to habitability of Mars and to help prepare for future human exploration of Mars. MSL was launched in November 2011 and arrived on August 6, 2012 on Mars, 100 years after the discovery of the cosmic rays by Victor Hess in 1912. Although not planned before RAD operated during nearly the complete cruise and provided the first time measurements inside a spacecraft comparable to a future manned spacecraft on the way to Mars. These data are published elsewhere,[14-17] and are not part of this paper, which concentrates on the Mars surface measurements.

II. Materials and Methods

MSL RAD sensor head consists of a silicon telescope (3 detectors) mounted on top of a CsI scintillator D and a plastic scintillator E (Figure 1). The silicon detector C of the telescope and the plastic scintillator F are used as coincidence for the scintillators D and E. Whereas all charged particles (protons and heavier ions up to Fe; charges $1 \leq Z \leq 26$) can be measured in the telescope, only for such particles which stop in E energy spectra can be provided; depending on the species this energy ranges from about 100 MeV /nuc for H and He up to 400 MeV/nuc for Fe. Neutral particles are detected in both in D and E, whereas detector D has a high efficiency for gamma rays and detector E has a high cross section for neutrons. The difference in detector response allows the separation of gamma rays and neutrons. Electron/ positron measurements are done with pulse height analysis. The energy coverage for the particles is also shown in Figure 1. For a detailed description see Ref. 18.

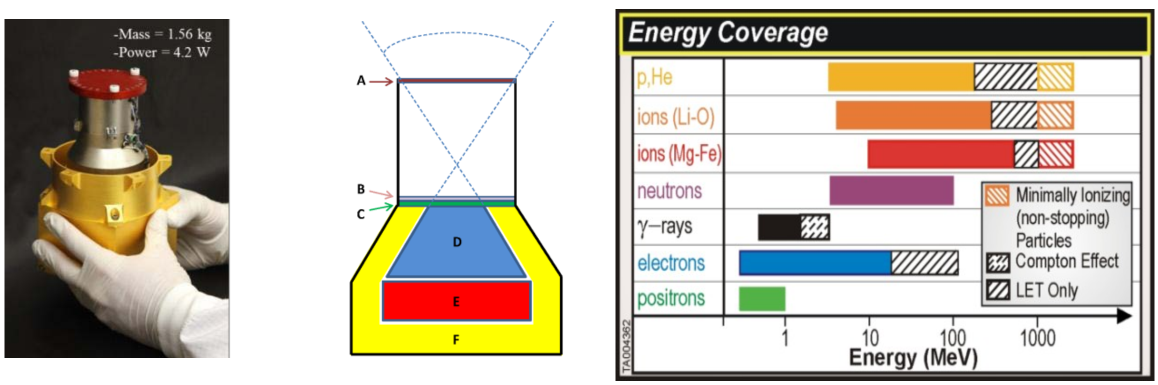


Figure 1: Left: MSL-RAD detector unit; middle: Schematics of the detector head; right: RAD measuring capability given as energy coverage per particle type.

The simulations presented in this work were performed with the Monte-Carlo simulation framework GEANT4.10. [19,20] The simulation geometry for the Martian atmosphere and soil was provided by the PLANETOCOSMICS tool (*http://cosray.unibe.ch /~laurent/planetocosmics/*). The simulated Martian atmosphere consisted of 95.7 mass % Carbon dioxide (CO_2), 2.7 mass % Nitrogen (N) and 1.6 mass % Argon (Ar) with a height of 90 km and a total column density of 22 g/cm^2. The column density was derived from the average pressure measured by MSL in the Gale crater. The primary input spectra for the transport calculation through the atmosphere were composed of galactic cosmic radiation nuclei from hydrogen to nickel using the model of Ref. 21 with a solar modulation parameter averaged over the first about 200 days of RAD measurements on the Martian surface (August 2012 to January 2013). Details about the simulation and a comprehensive comparison to other models and MSL-RAD measurements can be found in Ref. 22. The particle spectra at the Martian surface calculated with the method described above were converted to dose rates using fluence-to-dose conversion factors.

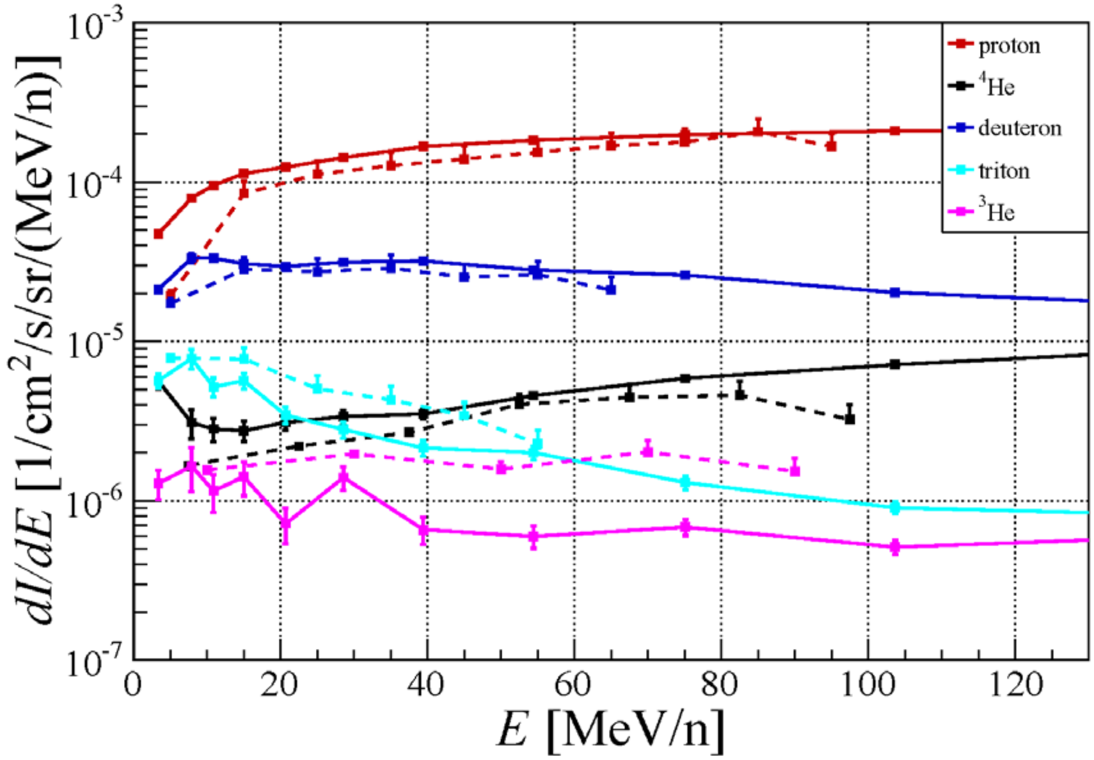
III. Results

The RAD instrument has been working from the time of landing until now for more than three years and is still accumulating data. Results are already published in several journals. [22-30] In this paper the comparison of GEANT4 model calculations using the galactic cosmic ray model of Ref. 21 with measurements of absorbed doses and heavy ion spectra by RAD is described.

From Figure 2 it can be seen that for protons (H) and Helium (^{4}He), as well deuterons (^{2}H) there is a very good agreement between calculations and measurements. For Tritium (^{3}H) and even more for the Helium isotope ^{3}He a large discrepancy is observed. Non-considered shielding effects by the Rover may be the reason for that. For the lower high Z groups the agreement is reasonable good, but for the Z= 9-13 group and for Fe considerable discrepancy is observed. For some energies this accounts for a factor of about 3 and even more. One reason for that is certainly statistics; therefore we expect better agreement when accumulating more data.

The absorbed dose measured in the E detector of MSL RAD accounts to 0.21±0.04 mGy/d. The E detector records all energy deposits by charged particles, same as tissue would do. For dose calculations an excellent agreement between measurements and calculations is demonstrated. This is presented in Figure 3 where the contribution of the different particle types to the dose is shown. Figure 3 also gives the calculations of dose equivalents, here the agreement between calculations and measurement differs much more. Since the risks attributed to radiation exposure are based on equivalent doses to the organs, we need to have a look on these quantities. The calculation of dose equivalents requires the determination of the mean radiobiological effectiveness of the radiation field, namely for humans the Quality Factor Q. [31-33] For MSL this factor is calculated based on coincidence events recorded in the A2 and the B detector. The measured energy deposit spectra are scaled by a constant factor to the energy deposit spectra in water, as tissue representative material. The dose equivalent of 0.64±0.12 mSv/d is calculated as the product between the measurement of the absorbed dose in the E detector and this mean quality factor. But, this Q is derived for a limited zenith angle range and may not describe the appropriate Q for the neutron contribution, which is underestimated using the Q deduced from energy deposition spectra of ionizing particles. The calculations predict a Q for neutrons greater than 10. RAD measurements result in a mean Q of about 4 for neutrons of a limited energy range.[26] However, calibrations for neutrons of higher energies up to 100 MeV are still missing. This calls beside the proper treatment of other species like electrons and positrons for a more detailed investigation of the E detector response. Saying this it should be noted that more than one third in the dose equivalent calculation is due to the neutron component. Taking the above statements into account calculations of dose equivalent with GEANT 4 differ considerably from the results obtained so far for dose equivalents based on RAD measurements. Most of the equivalent dose is contributed by the light particles which are enhanced through fragmentation of the heavy primaries in knock on reactions, for which we have a lack of information on appropriate cross sections for their production.

Figure 4 shows a calculation of the organ dose using fluence to dose conversion factors from Ref. 34; self-shielding of the human body reduces the exposure to the organs already by one third from $520 \mu Sv d^{-1}$ to about $380 \mu Sv d^{-1}$. Providing housing facility of several hundred g cm^{-2} shielding thickness the indoor exposure can be reduced to levels as existing on Earth.



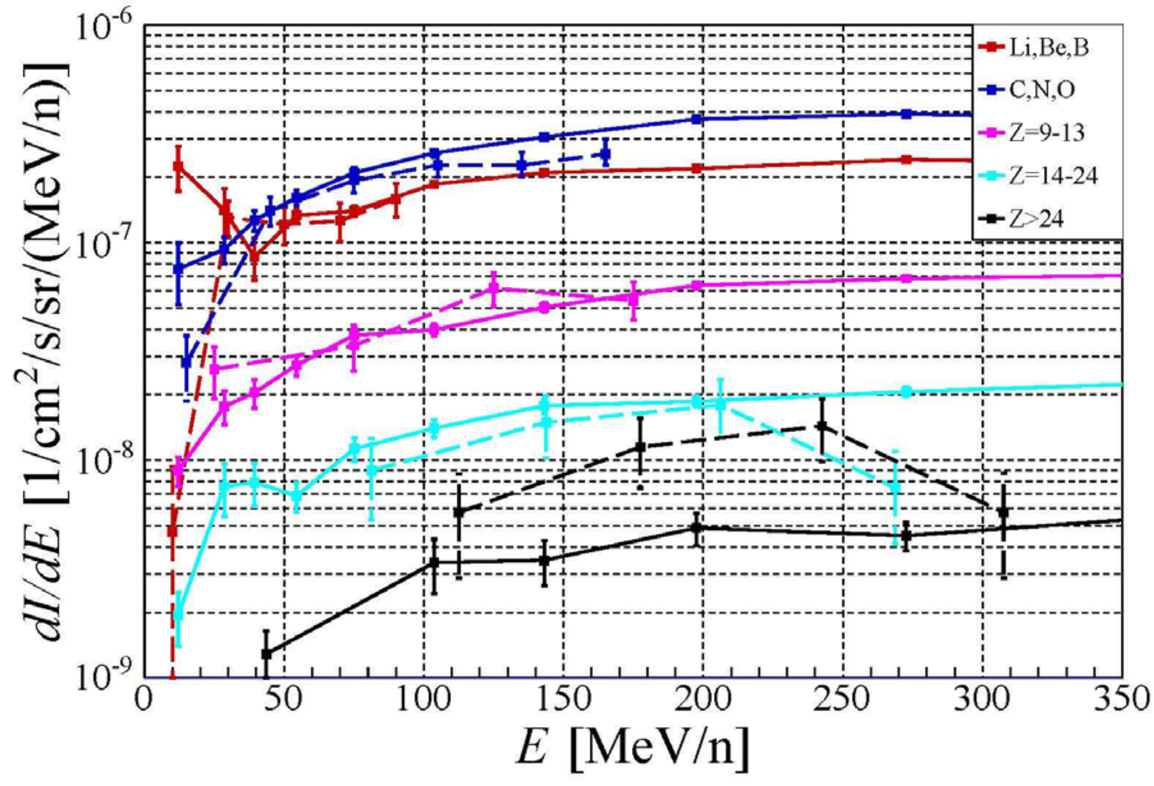


Figure 2: GEANT 4 calculations (solid lines) compared to measurements (dashed lines Ehresmann et al., 2014); upper graph is for low Z, lower graph for high Z.

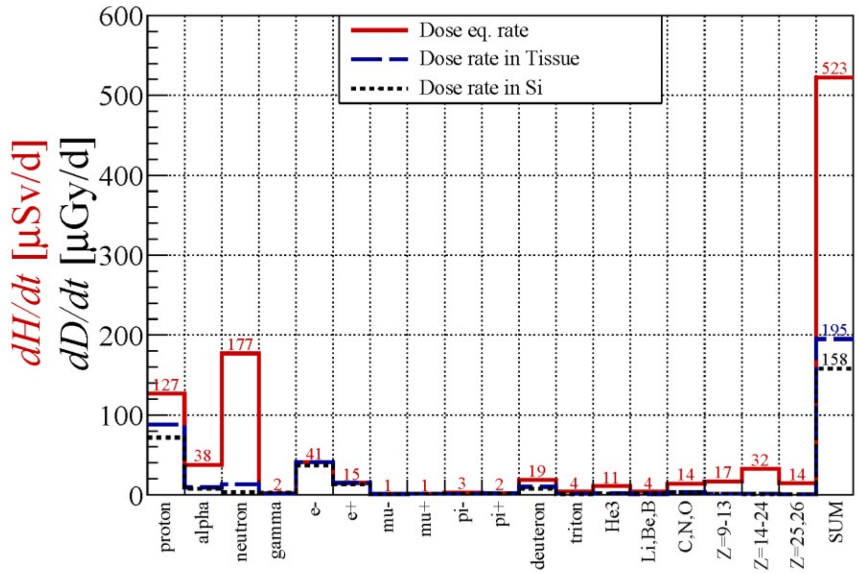


Figure 3: Dose and dose equivalent calculated using GEANT4 (0.195 mGy/d; 0.52 mSv/d, Q=2.7). For comparison: total dose measurement and dose equivalent based on RAD measurements in the E detector are 0.205 ±0.04 mGy/d and 0.64±0.12 mSv/d, respectively, using the quality factor Q=3.1±0.3 based on linear energy transfer measurements from the RAD silicon telescope.

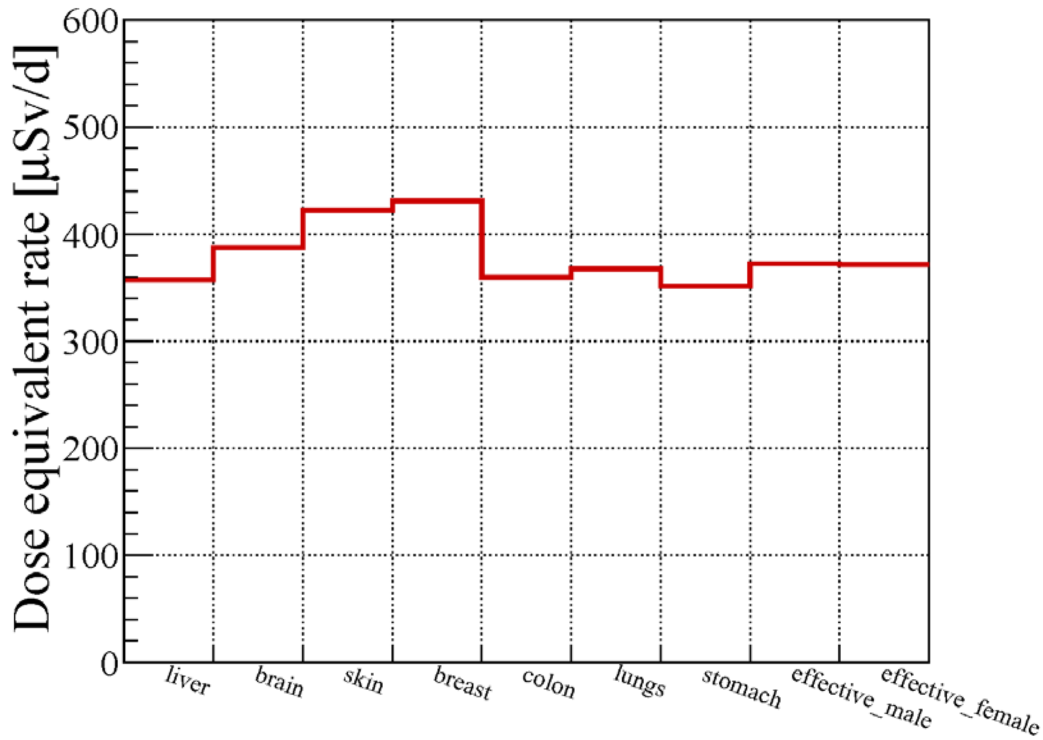


Figure 4: Calculated organ doses and effective dose equivalent per day for an Astronaut walking on the Mars surface.

IV. Conclusions

RAD measurements are used as a benchmark for models. Applying GEANT4 a good agreement between measurements and calculation is achieved for absorbed doses. For dose equivalents considerable differences are observed between calculations and measurements which will be subject to further studies. Also disagreements in the energy spectra were observed with a factor up to three for the heavier particles. This is of greater importance when taking into account that the concept of mean dose is only a rough approximation describing the effects of heavy ions in tissue by introducing high uncertainties in risk calculations.

In a recently published intercomparison it is shown that most of the advanced transport models like PHITS and HZETRN/OLTARIS are comparable in terms of calculated doses but differ significantly in some of the predicted particle spectra.[22] Model selection in GEANT4 may cause differences in calculated exposures up to 20%. In addition the contribution of neutrons to the dose may change significantly.

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