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Measurements of the neutron spectrum in transit to Mars on the Mars Science Laboratory

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A B S T R A C T

The Mars Science Laboratory spacecraft, containing the Curiosity rover, was launched to Mars on 26 November 2011. Although designed for measuring the radiation on the surface of Mars, the Radiation Assessment Detector (RAD) measured the radiation environment inside the spacecraft during most of the 253-day, 560-million-kilometer cruise to Mars. An important factor for determining the biological impact of the radiation environment inside the spacecraft is the specific contribution of neutrons with their high biological effectiveness. We apply an inversion method (based on a maximum-likelihood estimation) to calculate the neutron and gamma spectra from the RAD neutral particle measurements. The measured neutron spectrum (12–436 MeV) translates into a radiation dose rate of 3.8 ± 1.2 µGy/day and a dose equivalent of 19 ± 5 µSv/day. Extrapolating the measured spectrum (0.1–1000 MeV), we find that the total neutron-induced dose rate is 6 ± 2 µGy/day and the dose equivalent rate is 30 ± 10 µSv/day. For a 360 day round-trip from Earth to Mars with comparable shielding, this translates into a neutron induced dose equivalent of about 11 ± 4 mSv.

1. Introduction

The Mars Science Laboratory (MSL) mission was launched on November 26, 2011 and landed on Mars on August 6, 2012 after a 253-day cruise. On board the rover Curiosity is the Radiation Assessment Detector (RAD) which has been designed to "fully characterize the Martian radiation environment" (Hassler et al., 2012). However, the cruise to Mars was a unique opportunity to measure the radiation environment inside a spacecraft for future manned missions to Mars. Therefore RAD was operated during most of the cruise from Earth to Mars, gathering the first science data of Curiosity's mission. With the exception of some short interruptions, RAD provided a continuous radiation measurement from inside the spacecraft. RAD was initially operated on an 8-minute observation cadence, with a 100% duty cycle; as the distance between the spacecraft and Earth increased, it was necessary to reduce data volume, so that the cadence was increased to 16 minutes in late January 2012. The typical duty cycle from that time forward was 50%. Radiation dose, dose equivalent and linear energy transfer spectra inside the MSL spacecraft on its trip to Mars have been presented in Zeitlin et al. (2013).

The innovative design of RAD allows us to measure charged particles as well as gamma rays and neutrons. Obtaining charged particle spectra is fairly straightforward (Hassler et al., 2012; Ehresmann et al., 2014), but the multiple interaction processes of neutral particles result in a complex instrument response to neutral particles, which does not allow a similarly straightforward interpretation of neutral particle spectra. Measured neutral particle spectra do not give a direct picture of the real neutron and gamma spectra. Instead, a complex inversion method is required for their interpretation, as was presented in Köhler et al. (2014) for neutral particle measurements on the Martian surface. In this work we present the corresponding gamma ray and neutron measurements and spectra as they were present in the spacecraft during MSL's cruise phase.

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1.1. Motivation for measuring gamma and neutron spectra

For a manned mission to Mars, a large fraction of the radiation will be incurred during the cruise to and back from Mars (Zeitlin et al., 2013; Hassler et al., 2014). For instance, a 180 day one-way trip would result in a dose equivalent of 0.33 Sv. This is approximately 30% of the total expected dose rate for a return mission to Mars, consisting of a 180 day cruise to Mars, a 500-day surface stay and a 180-day return transit.

The contributions to the radiation environment inside the spacecraft are complex: primary Galactic Cosmic Rays (GCR) and Solar Energetic Particles (SEP) may pass through the spacecraft to deliver dose directly, or they may interact with the spacecraft material to produce secondary particles. As a result of the secondary particle production, there are more types of particles which form the radiation environment inside a spacecraft than outside, and neutrons are among those of greatest concern from the perspective of radiation protection. Interactions of GCR ions produce neutrons over a broad energy range from eV to GeV (Hess et al., 1959). Over most of that range, the biological damage associated with a given fluence of neutrons (expressed as dose equivalent per unit fluence) is modest, comparable to or less than that caused by the same fluence of charged particles. But neutron fluences increase with shielding depth and can be quite large. The fractional contribution of neutrons to dose equivalent increases with shielding depth (Simonsen et al., 2000), as charged particles either range out or undergo nuclear interactions. At large depths, such as in a habitat buried a few meters below the Martian surface, the neutron contribution may approach 50%. Furthermore, biological effects of neutron exposure are highly uncertain (Durante and Cucinotta, 2011), especially high above the fission energies and the 14-MeV Deuterium–Tritium energy where most neutron radiobiology experiments have been conducted. The neutron radiation inside the spacecraft is almost completely generated as secondary particles of GCR spacecraft interaction. Because of the finite lifetime of neutrons there is only a very low flux of solar neutrons at 1 AU (Feldman et al., 2010; Share et al., 2011). To our knowledge, this work presents one of the few high-energy neutron measurements in space.

1.2. The MSL spacecraft

The RAD instrument is mounted beneath the top deck of the rover Curiosity, which was inside the MSL spacecraft on its trip to Mars. Curiosity was located beneath the descent stage and above the heat shield, which provide additional shielding against the deep space radiation environment. Because secondary particles are produced in the shielding, knowledge thereof is crucial for estimating the contribution of neutral particles to the cruise radiation environment. A simplified model of the shielding of the upper hemisphere around RAD was created by Shawn King at the Jet Propulsion Laboratory, as shown in Fig. 1. Note that shielding values for polar angles above 40 degrees are considered to be approximations, because the simplified model focuses on the upward directed field of view pertinent to charged particle measurements. Most of the solid angle is merely lightly shielded (areal density < 10 g/cm^2), the remaining solid angle is shielded with varying depth, with up to 90 g/cm^2 for particle trajectories through a fuel tank filled with hydrazine. The lower hemisphere, which is not shown in Fig. 1, is much more uniform and dominated by the RAD electronic box (8 gm/cm^2) and the spacecraft heat shield (1.5 g/cm^2) (Zeitlin et al., 2013). Although a spacecraft designed for a human crew would most likely be designed to have a more homogeneous distribution of shielding with few lightly-shielded areas, the crew would be exposed to a similar composition of neutral particles, since those are produced in the shielding itself.

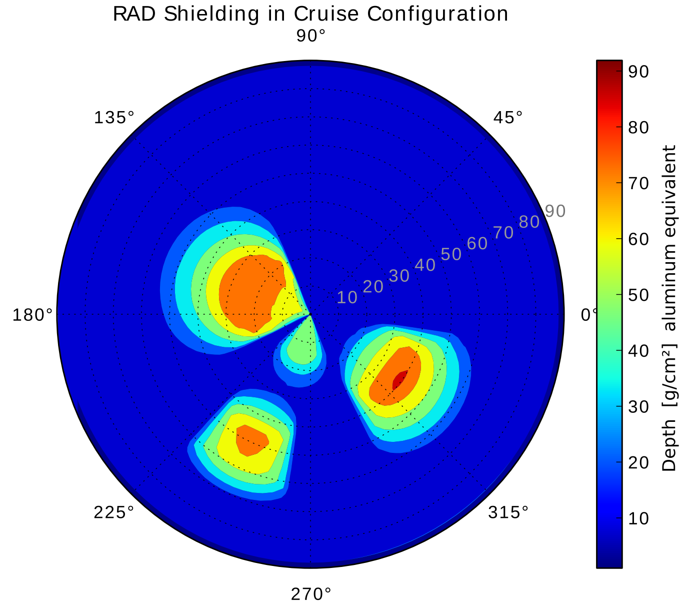

Fig. 1. Approximate representation of the shielding distribution. The center corresponds to the field of view direction of the RAD charged particle telescope, which was looking towards the sun during most of the cruise phase. Shielding depths are given in g cm^{-2} of aluminum equivalent shielding depth. Note that shielding values for polar angles above 40 degree are merely approximations, because the simplified model focuses on the upward directed field of view.

The available information is far from sufficient to create a detailed simulation of the gamma and neutron production through GCR spacecraft interaction. E.g., the exact composition of the shielding and the position of different elements such as the hydrazine tanks or the parachute are not known to us. Therefore, we can not attempt a quantitative simulation of the GCR induced neutron and gamma spectra, but rather a simulation to estimate the expected shapes of the gamma and neutron spectra induced by the interaction of GCR on aluminum and GCR on hydrazine.

2. Neutral particle measurements with RAD

The RAD instrument houses several detectors for charged and neutral particle measurement. Charged particles are measured by three silicon detectors (A, B, C), followed by a Tl-doped cesium iodide scintillator (D), neutral particles are measured by the combination of D and a plastic scintillator (E). The D scintillator is highly sensitive to gamma rays, the E detector is highly sensitive to neutrons. Both scintillators are enclosed by an anticoincidence (C, F) to reject charged particles. A detailed overview is given in Hassler et al. (2012), Fig. 2 shows a schematic view of the instrument. Each event is analyzed via pulse-height analysis on board. The events are classified according to a priority scheme and only a subset of the measured events is sent back to Earth together with scaling factors. The scaling factors can be used to reconstruct the measurement (Hassler et al., 2012).

2.1. Mathematical background

As explained in Köhler et al. (2014), the charged particles that are stopped by the scintillators in RAD deposit their full energy. In contrast, neutral particles do not necessarily stop in either detector and can create an energy deposit which is randomly distributed, ranging from zero up to their incident energy. This makes the measurement of neutral particle spectra very difficult. Further problems arise from the fact that the D detector is not only sensitive to gamma rays, but also to neutrons, albeit to a lesser degree.