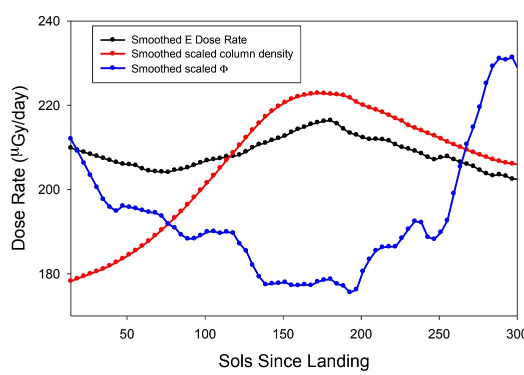
NEW RESULTS FROM THE MSL-RAD EXPERIMENT ON CURIOSITY, C. Zeitlin[1], D. M. Hassler[2], R. S. Wimmer-Schweingruber[3], J. Köhler[3], S. C. R. Rafkin[2], B. Ehresmann[2], J. Guo[3], S. Böttcher[3], E. Böhm[3], C. Martin[3], G. Reitz[4], A. Posner[5], D. E. Brinza[6], [1]Southwest Research Institute Earth, Oceans, Space Division, Durham, NH, cary.zeitlin@swri.org, [2]Southwest Research Institute, Boulder, CO, [3]Kiel University, Kiel, Germany, [4]German Aerospace Agency Cologne, Germany, [5]NASA Headquarters, Washington, DC, [6]California Institute of Technology, Pasadena, CA

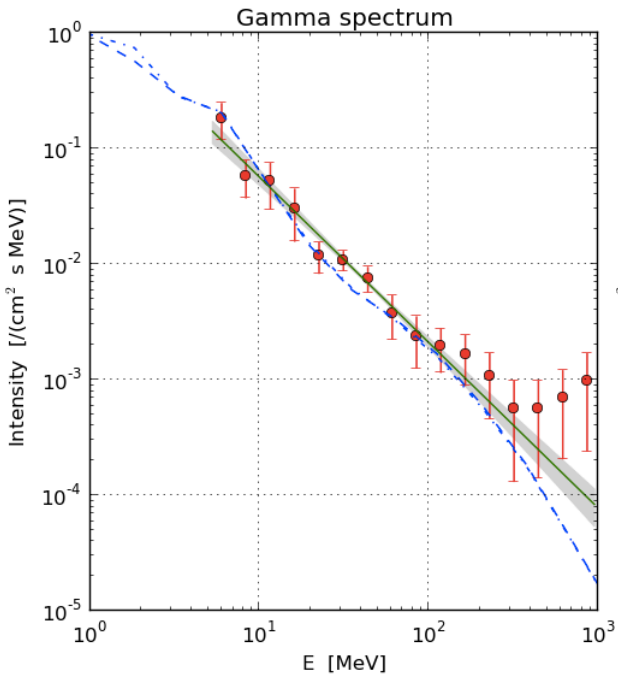
Introduction: RAD, the Radiation Assessment Detector [1], has been operating successfully on Mars since Curiosity landed in August 2012. RAD is an energetic particle detector capable of measuring all charged particles that contribute to the radiation health risks that will be faced by future explorers to the Red Planet. In addition, RAD can measure high-energy neutrons (from about 8 to 300 MeV) that also make important contributions to the radiation hazard. RAD is used as a dosimeter [2, 3] for both charged and neutral particles [4], and is also a spectrometer that measures charged particle fluxes as functions of species and energy [5]. The energy range of these measurements is constrained by the low mass of RAD, but spectra in the range from about 10 to 100 MeV/nuc are measured for protons and helium nuclei, with higher energy ranges for heavier particles. In addition to the data obtained on the surface of Mars, RAD measured the radiation environment inside the MSL spacecraft during the transit to Mars, providing an additional important data set for planning of future missions that involve travel in shielded vehicles through interplanetary space. RAD data will play a key role in the validation of radiation transport models used to predict future exposures in various mission scenarios. Of particular importance are detailed comparisons between model predictions and spectral data for various particle types (e.g., protons, neutrons, helium ions, and heavier ions).

Highlights from the Surface Mission: MSL landed on Mars at a time that had been predicted to be near the maximum of Cycle 24 solar activity. However, the Cycle 24 maximum has proven to be extraordinarily weak by historical standards, resulting in GCR dose rates that are higher than would have been expected based on previous cycles. Data taken over the first 450 sols (24 hours and 37 minutes per sol) indicate that the GCR dose rate on the surface is sensitive both to changes in the large-scale heliosphere and to local changes in atmospheric pressure in Gale Crater. Smoothed data with arbitrary units in the figure below illustrate these trends. In that time, two Solar Energetic Particle events have occurred with sufficiently hard spectra to produce a detectable increase in the charged particle flux on the surface. Given that RAD is shielded by about 20 g cm^{-2} of CO_2, these events must have accelerated protons to energies above 150 MeV. Several other solar events have been indirectly observed in the form of Forbush decreases, which are suppressions of energetic particles caused by short-term changes in the interplanetary magnetic field arising from Coronal Mass Ejections.

RAD has also observed clear diurnal signals [5] in total dose, heavy ion flux, and neutron flux. These diurnal effects are directly attributable to the significant daily changes in the column depth of atmosphere above RAD. Deconvolution of neutral particle spectra into gamma-ray and neutron spectra has been performed for data taken over the first 100 sols [4] and will be presented. The dose equivalent contribution from neutrons in the range of RAD's sensitivity is found to be about 10% of the total. The (scaled and smoothed) column density data shown here are based on atmospheric pressure measurements made by the REMS instrument [7] aboard Curiosity. The solar modulation parameter Φ has been determined from data provided by the Oulu neutron monitor facility [8].



Neutral Particle Analysis and Dose Contribution. RAD contains a high-density inorganic scintillator made from cesium iodide, referred to as the "D" detector. This detector is sensitive to gamma-rays and neutrons. The presence of the MMRTG on Curiosity requires us to operate it with a high energy threshold. RAD also contains a plastic scintillator ("E") that is sensitive to neutrons. A mathetmatical technique has been developed in which the neutral-particle spectra recorded in these two detectors are simultaneously inverted using calculated response functions in order to obtain gamma-ray and neutron spectra. The method and results are given in Ref. [4]. Once we have the spectrum of neutron flux vs. energy, the appropriate



weighting factors can be applied to calculate both the dose and dose equivalent arising from neutrons on the Martian surface. The measured dose rate is found to be 14 ± 4 μGy/day, roughly 7% of the total, and the dose equivalent rate is found to be 61 ± 15 μSv/day, about 10% of the total. It is important to note that, due to the compact size of RAD, the sensitivity of E for neutrons is limited to those that make relatively large energy deposits, which translates in to a threshold energy of about 8 MeV. Lower-energy neutrons, including those coming from the surface (so-called leakage or albedo neutrons) are not measured by RAD and may contribute significantly to dose and dose equivalent.

Implications for Future Human Exploration: The scientific literature contains a number of predictions for radiation dose rates on Mars. To some extent these depend on the assumptions made about the time in the solar cycle (i.e., solar modulation), atmospheric shielding, and other variables. The highest predicted dose rates are about four times higher than the lowest. RAD measurements are approximately in the middle of the range. In the NASA Design Reference Mission, one of the more feasible profiles calls for an outward transit time of about 180 days, about 500 days on the surface, and a return trip of 180 days. Because of the measurements made by RAD during its cruise to Mars and on the surface, we can make the first data-based estimate of the exposure that a human crew would receive in this scenario. In radiation protection, risk is related not to dose, but to dose equivalent, which is a quantity derived both from dose and from the particle spectrum. In cruise, the dose equivalent rate from GCR was found to be 1.84 mSv/day, and on the surface the rate is 0.64 mSv/day. A cruise duration of 360 days would, under similar heliospheric and shielding conditions, be expected to give a total of 660 mSv, while 500 days on the surface would give 320 mSv, for a combined total of about 1 Sv. At present, epidemiology based on acute human exposures to sparsely-ionizing radiation forms the basis for estimating health risks due to radiation exposure. The situation in space is quite different: astronauts receive a chronic low-dose exposure to a mixture of sparely- and densely-ionizing radiation. In conventional terms, a 1 Sv exposure corresponds to roughly a 5% increase in the probability of an exposed individual's lifetime cancer mortality risk, but it is not yet clear what risk levels are associated with a 1 Sv exposure to space radiation incurred over a period of many months.

References: [1] D. M. Hassler et al. (2012), *Space Science Reviews* 170.1-4, 503-558. [2] C. Zeitlin et al. (2013), *Science* 340.6136, 1080-1084. [3] D. M. Hassler et al. (2014), *Science* 343 6169. [4] J. Köhler et al. (2014), *JGR 119* 594-603. [5] B. Ehresmann et al. (2014), *JGR 119* 468-479. [6] S. C. R. Rafkin, *JGR*, in press. [7] J. Gomez-Elvira et al., *Space Science Reviews* 170.1-4, 583-640. [8] I. Usoskin et al. (2005), *JGR 110*, A12108.