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Variations of dose rate observed by MSL/RAD in transit to Mars

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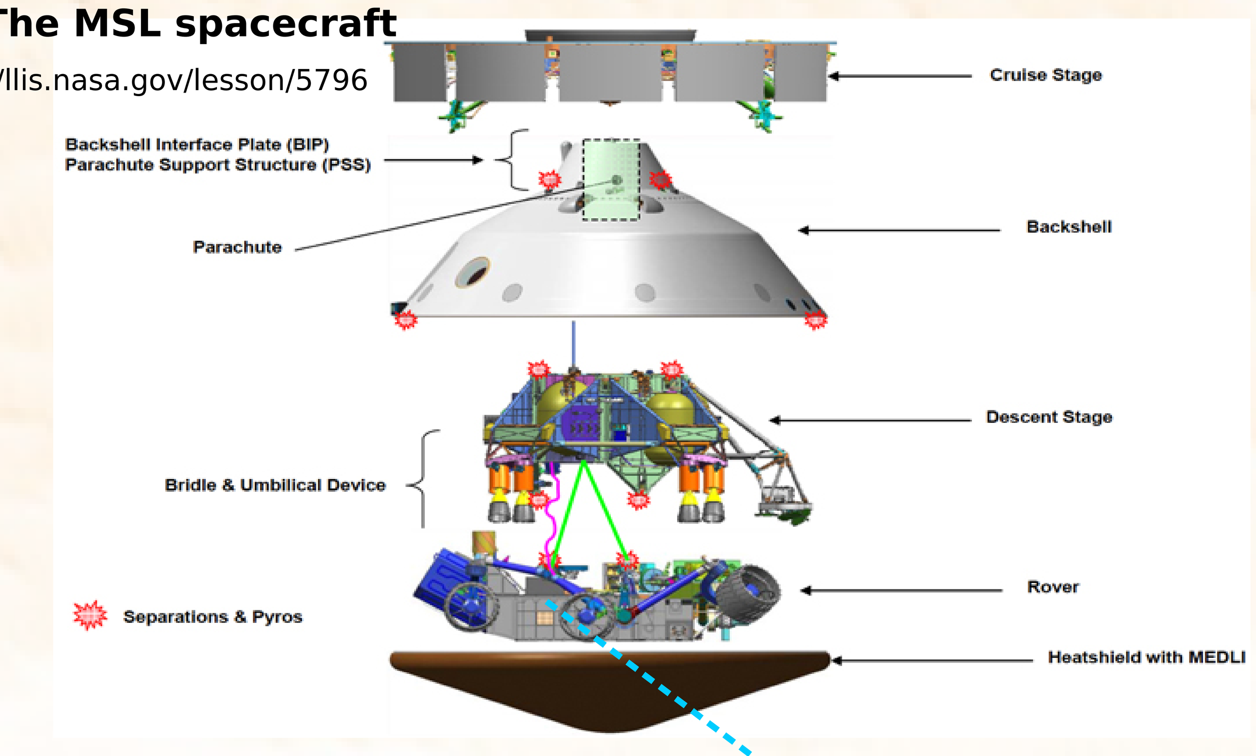
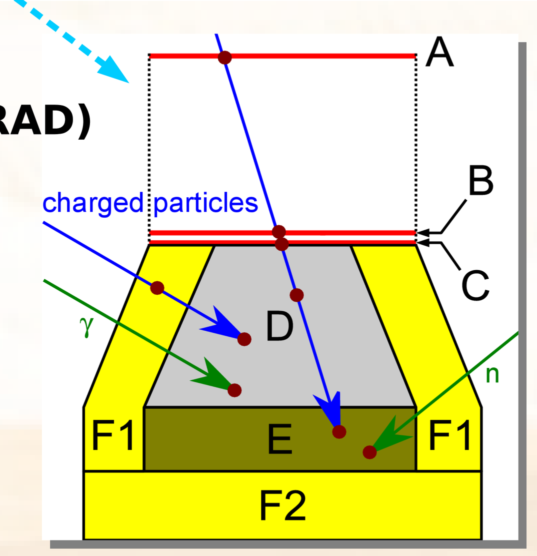
- **Motivation:**
  To predict the cruise radiation environment related to future human missions to Mars, the correlation between solar modulation potential and the dose rate measured by the Radiation Assessment Detector (RAD) has been analyzed and empirical models have been employed to quantify this correlation.
- **Methods:**
- The instrument RAD, onboard Mars Science Laboratory's (MSL) rover Curiosity, measures a broad spectrum of energetic particles along with the radiation dose rate during the 253-day cruise phase as well as on the surface of Mars. With these first ever measurements inside a spacecraft from Earth to Mars, RAD observed the impulsive enhancement of dose rate during solar particle events as well as a gradual evolution of the galactic cosmic ray (GCR) induced radiation dose rate due to the modulation of the primary GCR flux by the solar magnetic field, which correlates with long-term solar activities and heliospheric rotation.
- **Results:**
  We analyzed the dependence of the dose rate measured by RAD on solar modulation potentials and estimated the dose rate and dose equivalent under different solar modulation conditions. These estimations help us to have approximate predictions of the cruise radiation environment, such as the accumulated dose equivalent associated with future human missions to Mars.
- **Conclusions:**
  The predicted dose equivalent rate during solar maximum conditions could be as low as one-fourth of the current RAD cruise measurement. However, future measurements during solar maximum and minimum periods are essential to validate our estimations.

Fig. 1: The MSL spacecraft

From http://llis.nasa.gov/lesson/5796



The Radiation Assessment Detector (RAD)



- RAD is an energetic particle detector designed to measure **galactic cosmic rays**, **solar energetic particles**, **secondary neutrons**, and other secondary particles.
- During the cruise, RAD measured a mix of primary and secondary particles. The latter are produced by primary particles via nuclear or electromagnetic interactions as they traverse the spacecraft.
- RAD **dose measurements** were taken using two concurrent methods: one with silicon detector B and the other one with plastic scintillator E.

Fig. 2: Schematic view of the RAD instrument, consisting of three silicon diodes, A,B,and C(each 300 micro meter thick), a caesium iodide scintillator (D) and a plastic scintillator (E). Both D and E are surrounded by a plastic anticoincidence (F). From Guo et al. 2015 A&A.

GCR-induced dose rate modulated by the solar activity

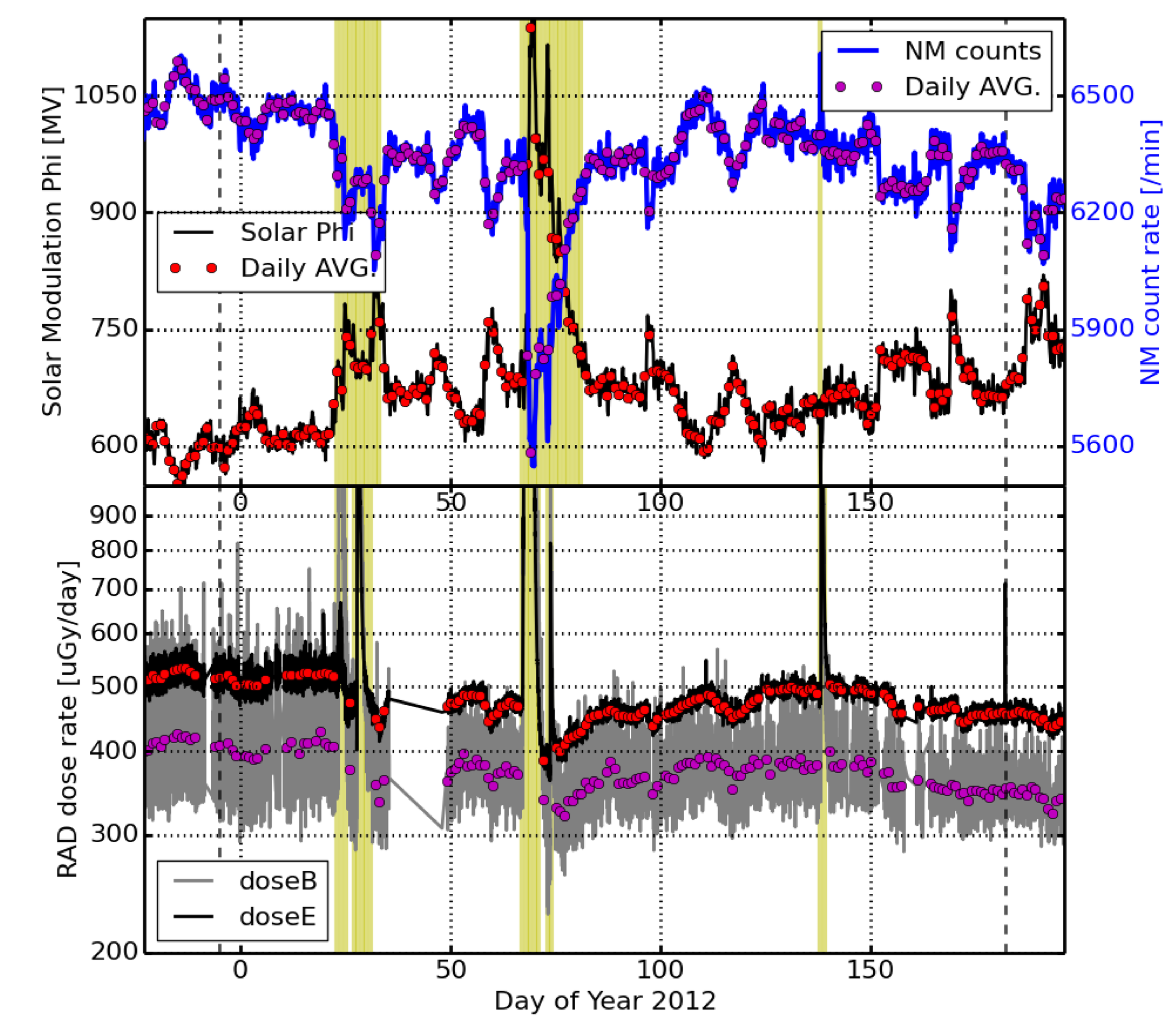


Fig.3: ***Top***: The blue line shows the Oulu neutron monitor count rate recorded during the time of MSL's cruise to Mars and the daily averaged values are shown as magenta dots. The black line shows the solar modulation potential Φ, a commonly used parameter of heliospheric modulation (Usoskin et al. 2005), derived from the neutron monitor count rates and its daily average is shown as red dots. The RAD observed SEPs are highlighted in yellow shaded areas in which the data are not considered in the GCR related correlation study. ***Bottom***: dose rate recorded by RAD in silicon detector B (gray curve) and in plastic scintillator E(tissue-equivalent, black curve). Their daily averaged values are plotted as solid dots in magenta and red. From Guo et al. 2015 A&A.

During most of the cruise phase the MSL spacecraft was well connected with the Earth via the Parker spiral magnetic field, and the data clearly indicate an anti-correlation between the variation of the RAD dose rate and the solar modulation potential Φ, with **the correlation coefficient being -0.8**.

Empirically modeling the correlation between solar modulation and cruise dose rate

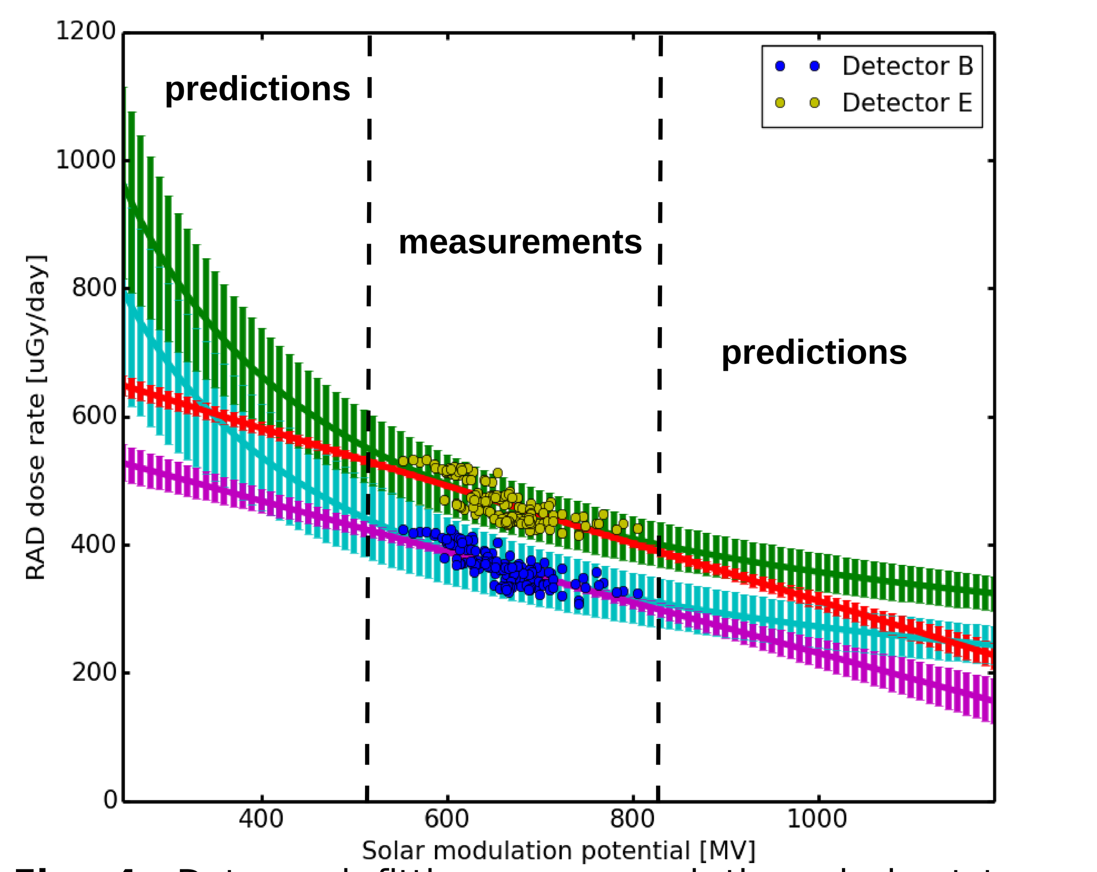


Fig. 4. Data and fittings processed through bootstrap Monte Carlo simulations of the variations of the RAD dose rate and the solar modulation during the cruise to Mars. The red/magenta lines represent the linear fits (Eq. 1). The green/cyan lines show the results of the nonlinear fits (Eq. 2). From Guo et al. 2015 A&A.

A quantitative study of the anticorrelation between solar modulation and dose rate is challenging because of the lack of analytic models. We employed two separate empirical models to describe this anticorrelation:

- A simple **linear** correlation described by a first order polynomial function is used to fit the daily average data, i.e.,

$$D = \beta_0 + \beta_1 \Phi \qquad [1]$$

where D is the RAD measured dose rate (either by detector B or E) in the unit of μGy/day and β1 in the unit of μGy/day/MV represents the linear relation between the changing of the solar modulation and the variance of observed dose rate.

- A **nonlinear** empirical model, which is often used in the analysis of neutron count rates (Usoskin et al. 2011) is:

$$D = \alpha_0 + \frac{\alpha_1}{\Phi + \alpha_2} \qquad [2]$$

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Predictions of the Radiation Environment (dose equivalent rate) under different solar modulation conditions

For evaluating the space radiation environment, dose equivalent rate, in Sieverts (Sv), is often derived from dose rate and can be assumed to be proportional to the risk of lifetime cancer induction. It can be approximately estimated to be <Q> × D, where D is the dose rate and <Q> is the average quality factor, which is a conventional parameter for radiation risk estimation. A value of 3.82 ± 0.25 was measured during MSL's cruise phase (Zeitlin et al. 2013). The extrapolated dose rate estimations at different modulation potential values, shown in Fig. 4, can therefore be used to evaluate the dose equivalent rate.

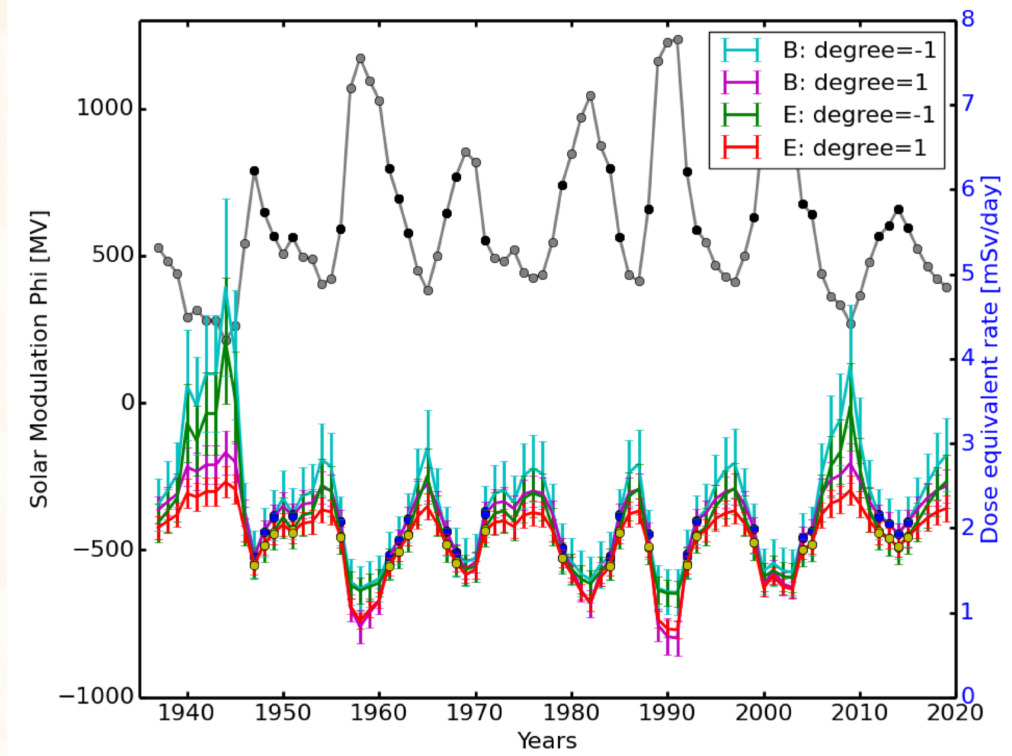

Fig.5: Annual average of reconstructed modulation potential since 1937 (gray line and dots with units on the left axis; Usoskin 2014) and estimated annual dose equivalent rate derived from different models and detectors (with units on the right axis). Cyan/Green line shows the dose equivalent values derived from the nonlinear model (Eq. 2) based on detector B/E data. Magenta/Red line represents the dose equivalent values derived from the linear model (Eq. 1) based on detector B/E data. Black, yellow, and blue dots represent the data within the range of modulation between 550 and 810 MV which the RAD cruise measurements covered. From Guo et al. 2015 A&A.

Discussions and Conclusions

- We presented the dose rate data collected by MSL/RAD during its cruise phase from Earth to Mars and analyzed its variations during solar quiet periods.
- The variation of the GCR-induced dose rate at MSL occurs nearly simultaneously with the variation in neutron monitor count rate at Earth and was mainly driven by changes in heliospheric conditions, with a correlation coefficient of about -0.8.
- A quantitative study of this anti-correlation has been carried out employing two empirical models, which fit the data equally well but with big discrepancies and uncertainties when extrapolated to extreme solar modulation potentials. **Therefore future measurements during solar minimum periods are necessary for improving the predictions at this range.**
- Total mission GCR dose equivalent can be estimated based on our measurements and predictions.
  - Considering a similar shielding condition, assuming a 180-day, one-way duration as a typical NASA's "Design Reference" Mars mission (Drake et al. 2010), we could estimate a crew taking a round trip to receive about 360 ± 180 mSv from GCRs under a high solar modulation condition (1200 MV).
  - The fastest round trip with on-orbit staging and existing propulsion technologies has been estimated to be a 195-day trip (120 days out, 75 days back with an extra, e.g., 14 days on the surface; Folta et al. 2012). This would result in an even smaller GCR-induced cruise dose equivalent during solar maximum: 195 ± 98 mSv.
  - However, this fast round-trip requires extra propulsion, which may result in a reduction of payload mass and a change of shielding conditions which would affect the generation of secondary particles and so as well the dose rates.