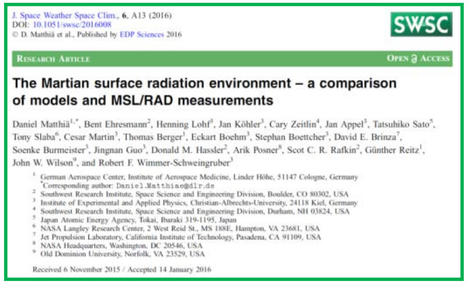
MSL-RAD
Summary of model calculations and comparison to RAD data

Daniel Matthiä

German Aerospace Center, Institute of Aerospace Medicine, Linder Höhe, 51147 Cologne, Germany

Overview

1. Update on the comparison of the calculated particle fluxes and dose rates with MSL-RAD data



J. Space Weather Space Clim., 6, A13 (2016)
DOI: 10.1051/swsc/2016008

SWSC

RESEARCH ARTICLE — OPEN ACCESS

The Martian surface radiation environment – a comparison of models and MSL/RAD measurements

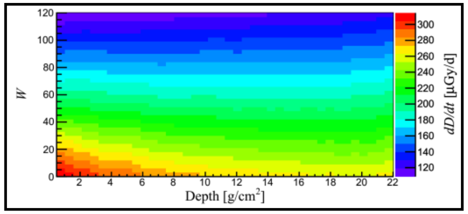
Daniel Matthiä[1,*], Bent Ehresmann[2], Henning Lohf[3], Jan Köhler[3], Cary Zeitlin[4], Jan Appel[3], Tatsuhiko Sato[5], Tony Slaba[6], Cesar Martin[3], Thomas Berger[1], Eckart Boehm[3], Stephan Boettcher[3], David E. Brinza[7], Soenke Burmeister[3], Jingnan Guo[3], Donald M. Hassler[2], Arik Posner[8], Scot C. R. Rafkin[2], Günther Reitz[1], John W. Wilson[9], and Robert F. Wimmer-Schweingruber[3]

[1] German Aerospace Center, Institute of Aerospace Medicine, Linder Höhe, 51147 Cologne, Germany
[*] Corresponding author: Daniel.Matthiae@dlr.de
[2] Southwest Research Institute, Space Science and Engineering Division, Boulder, CO 80302, USA
[3] Institute of Experimental and Applied Physics, Christian-Albrechts-University, 24118 Kiel, Germany
[4] Southwest Research Institute, Space Science and Engineering Division, Durham, NH 03824, USA
[5] Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan
[6] NASA Langley Research Center, 2 West Reid St., MS 188E, Hampton, VA 23681, USA
[7] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[8] NASA Headquarters, Washington, DC 20546, USA
[9] Old Dominion University, Norfolk, VA 23529, USA

Received 6 November 2015 / Accepted 14 January 2016

2. "1[st] Mars Space Radiation Modeling Workshop" held in June 2016 in Boulder

3. Development of a parameterized radiation model for the Martian atmosphere at DLR



1. Update on the comparison of calculation/MSL-RAD measurements

Update on the comparison of the calculated particle fluxes and dose rates with MSL-RAD data (Now published: Matthiä et al. SWSC 6, A13, 2016)

J. Space Weather Space Clim., **6**, A13 (2016)
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Setup for the simulations

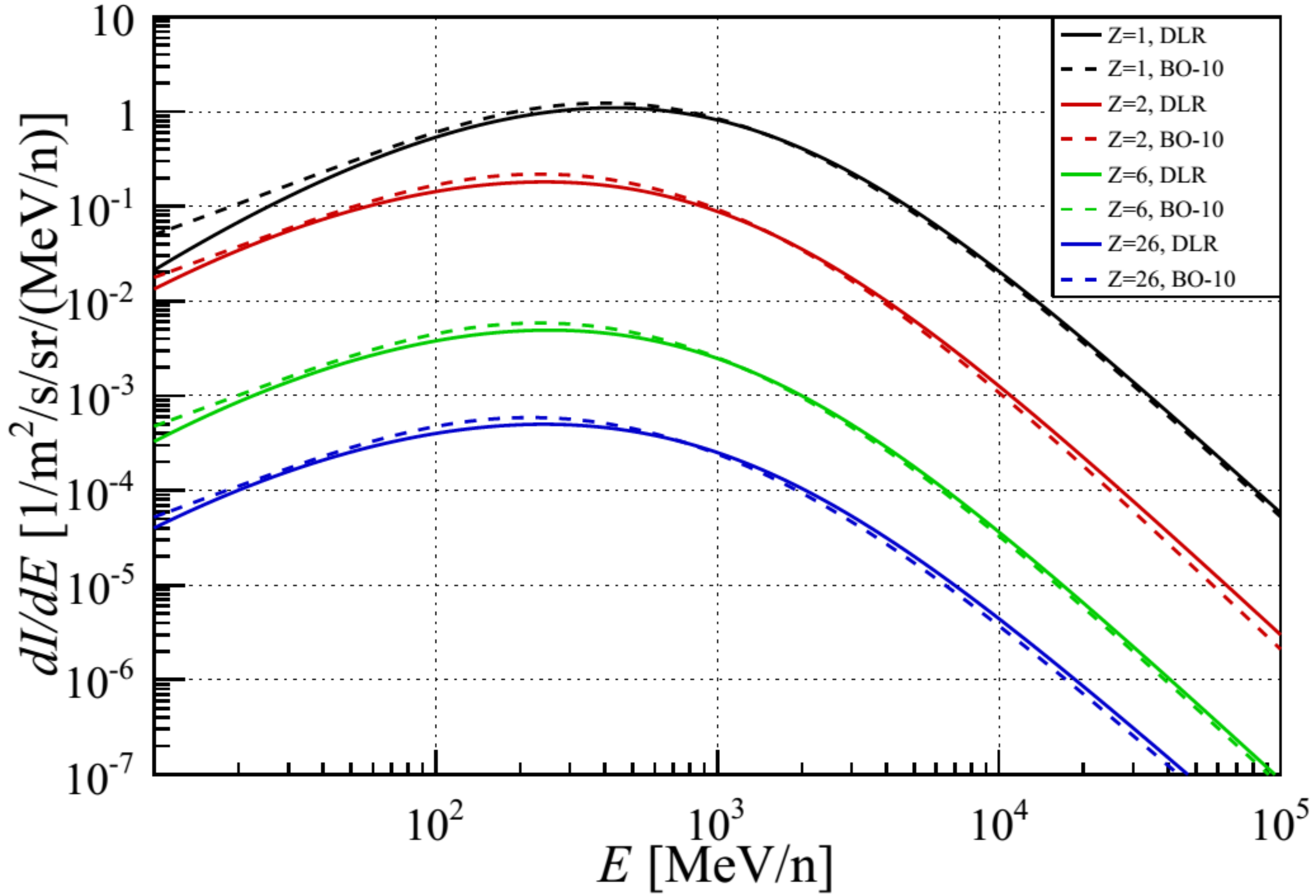
- **Atmosphere:**
  - 22 g/cm^2
  - Composition (mass %): 95.7% CO_2, 2.7% N_2,1.6% Ar (Mars-Gram 2001)
- **Soil:** ≥ 20m, composition from OLTARIS

Density: 1.7 g/cm^3

Defined in Terms of Molecular Percentages	
Formula	**Percentage(0 < p <= 100)**
O_2Si	51.2
Fe_2O_3	9.3
$Al_2CaK_2MgNa_2O_7$	32.1
H_2O	7.4
Total	**100.0**

- **GCR-Input:** DLR and Badhwar/O'Neill 2010:
  - 19. Aug. 2012 (DoY 232, 2012) – 17. Feb. 2013 (DoY 048, 2013) [182 days]
- **Particles: neutron** (10^{-8} MeV to 10^4MeV), **proton** (1MeV to 10^5 MeV), **gamma** (10^{-3} MeV to 10^4 MeV), **$e^{-,+}$** (10^{-3} MeV to 10^4 MeV), **deuteron, triton, ^{3}He, ^{4}He, Li/Be/B, C/N/O, Z=9-13, Z≥14** (all 1 MeV/n to 10^5 MeV/n)
- 4π, zenith angle < 30°

GCR input spectra: DLR and Badhwar/O'Neill 2010

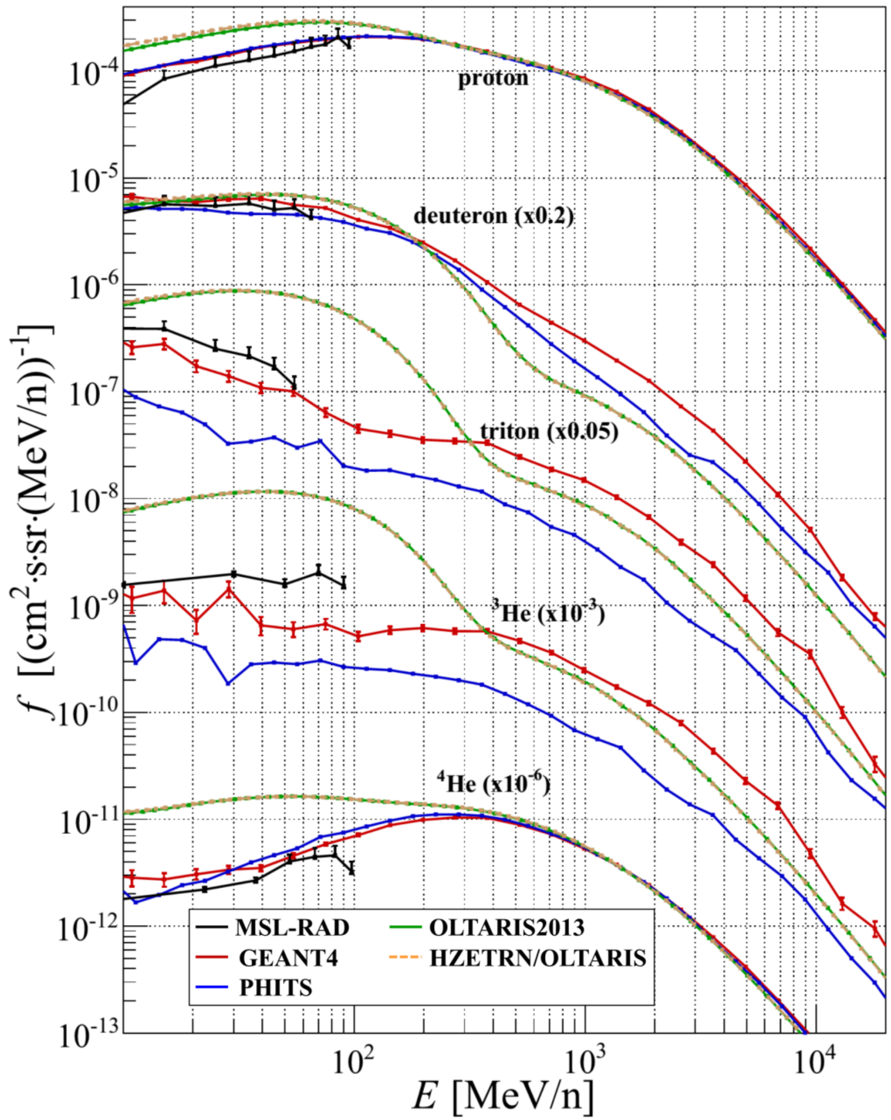


19. August 2012 (DoY 232, 2012) until 17. February 2013 (DoY 048, 2013) [182 days]

Proton, deuteron, triton, ^{3}He, ^{4}He Summary

- Zenith angle ≤30°
- **MSL-RAD data:** *Ehresmann et al. 2014*
- GEANT4, PHITS, OLTARIS2013, HZETRN/OLTARIS

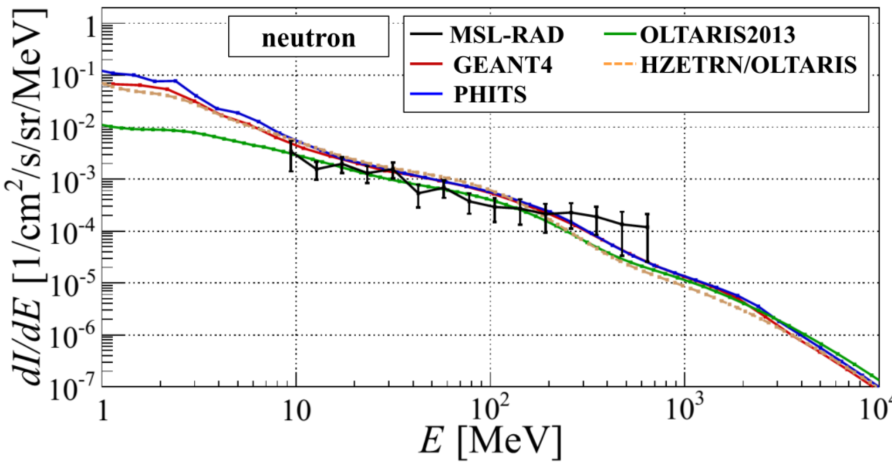
Matthiä et al. SWSC 6, A13 (2016)

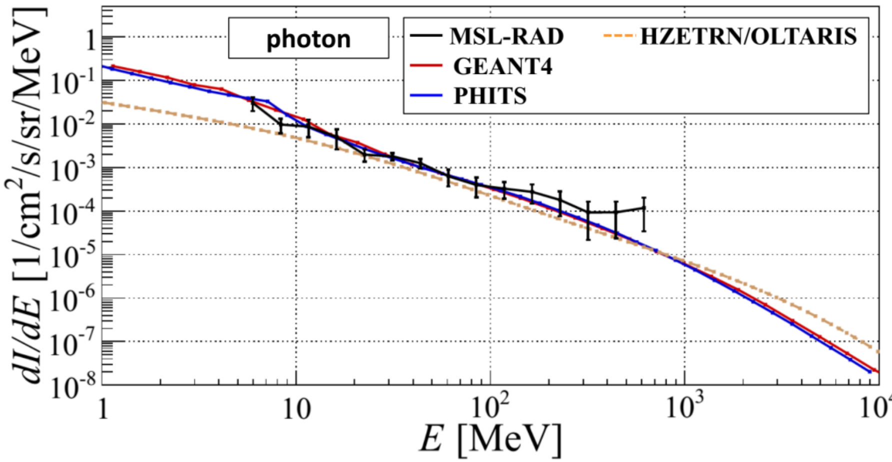


Neutron and photon

- **MSL-RAD data:** *Köhler et al. 2014*
- **Neutrons:** (GEANT4, PHITS, HZETRN, OLTARIS2013)
  - Good agreement above 1GeV
  - Lower neutron fluxes from OLTARIS2013 below 1GeV (upward fluxes are missing)
- **Photons:**
  - Good agreement GEANT4/PHITS
  - HZETRN significantly lower (higher) at energies < 10MeV (>1GeV)

Matthiä et al. SWSC 6, A13 (2016)





Matthiä et al. SWSC 6, A13 (2016)

Comparison of calculated and measured dose rates

	MSL-RAD [Hassler et al., 2014]	GEANT 4.10.p02	PHITS	OLTARIS2013	HZETRN/ OLTARIS
absorbed dose rate [mGy/d]	**0.21 ± 0.04**	**0.19**	**0.20**	**0.16**	**0.18**
dose equivalent rate [mSv/d]	**0.64 ± 0.12**	**0.52**	**0.60**	**0.52**	**0.54**
Quality factor	**3.05 ± 0.26**	**2.7 (3.0)**	**3.0 (3.4)**	**3.2**	**3.0 (3.2)**

NOTE: Values in parenthesis are the derived quality factors for a restricted zenith angle θ<30°.

2. "1st Mars Space Radiation Modeling Workshop" held in June 2016 in Boulder

1st Mars Space Radiation Modeling Workshop

- Organised by SWRI, NASA, DLR, CAU
- At SWRI, Boulder, June 28 - 30, 2016
- **Goal:** Extension of model comparison
  - new set of experimental data,
  - **15 Nov 2015 – 15 Jan 2016**
- Similar approach as before

- Models:
  - FLUKA (K. Lee, NASA)
  - GEANT4 (D. Matthiä, DLR) →
  - GEANT4/HZETRN (A. Firan, R. Rios, NASA)
  - HETC-HEDS (W. de Wet, L. Townsend; Univ. of Tennessee) →
  - HZETRN (T. Slaba, NASA) →
  - MCNP6 (L. Heilbronn, H. Ratliff, M. Smith; Univ. of Tennessee) →
  - PHITS (J. Flores-McLaughlin, NASA) →

comparison paper submitted to LSSR

Modeling workshop papers, accepted in LSSR

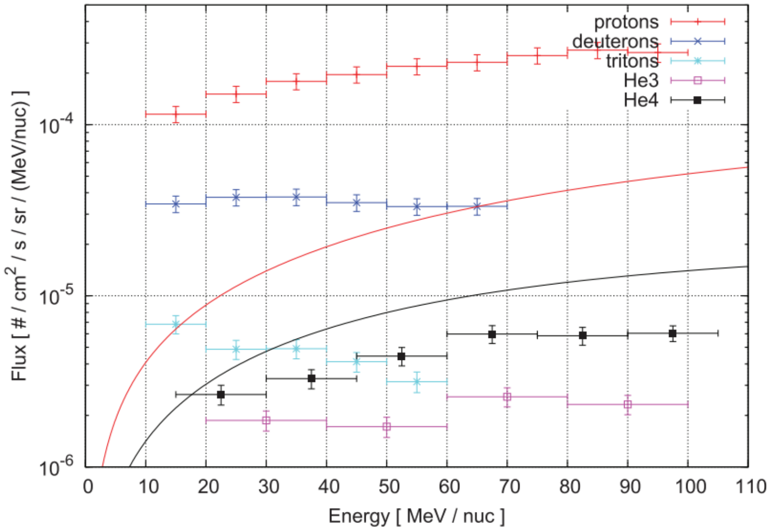
- Introduction
  - **Hassler et al.**, "Mars science laboratory radiation assessment detector (MSL/RAD) modeling workshop proceedings"
- Measurements:
  - **Ehresmann et al.**, "The charged particle radiation environment on Mars measured by MSL/RAD from November 15, 2015 to January 15, 2016"
  - **Guo et al.**, "Measurements of the neutral particle spectra on Mars by MSL/RAD from 2015-11-15 to 2016-01-15"
- Models:
  - **de Wet & Townsend**, "A calculation of the radiation environment on the Martian surface" (HETC-HEDS)
  - **Flores-McLaughlin**, "Radiation transport simulation of the Martian GCR surface flux and dose estimation using spherical geometry in **PHITS** compared to MSL-RAD measurements"
  - **Matthiä & Berger**, "The radiation environment on the surface of Mars – Numerical calculations of the galactic component with **GEANT4/PLANETOCOSMICS**"
  - **Ratliff et al.**, "Simulation of the GCR spectrum in the Mars curiosity rover's RAD detector using **MCNP6**"
  - **Slaba & Stoffle**, "Evaluation of **HZETRN** on the Martian surface: Sensitivity tests and model results"
- Summary:
  - **Matthiä et al.**, "The radiation environment on the surface of Mars - Summary of model calculations and comparison to RAD data"

Highlights from *Ehresmann et al. (2017), "The charged particle radiation environment on Mars measured by MSL/RAD from November 15, 2015 to January 15, 2016"*

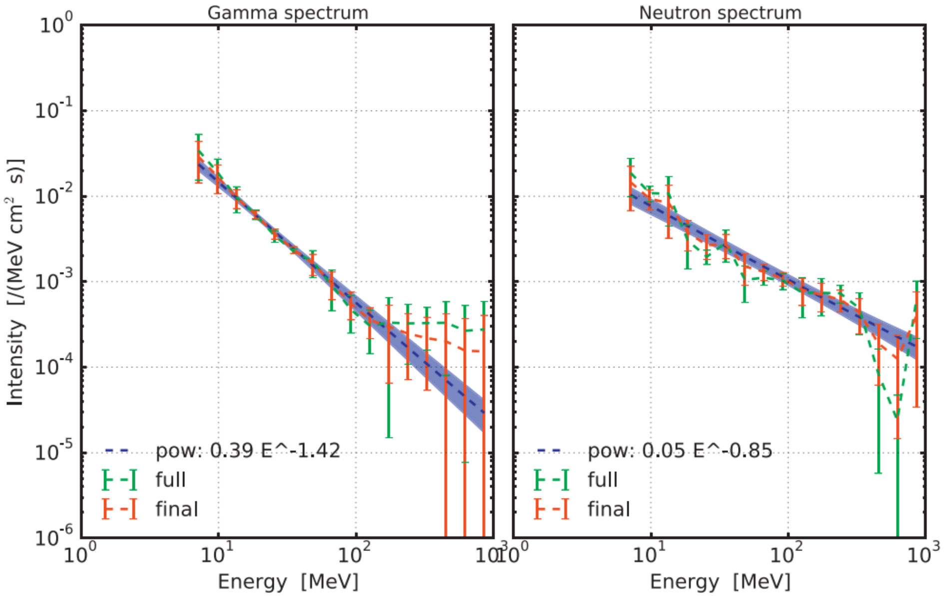
- Measured integral charged particle fluxes

Charge number and ion species	RAD fluxes [cm^{-2} s^{-1} sr^{-1}]	Minimum energy [MeV/nuc]	GCR flux [cm^{-2} s^{-1} sr^{-1}]
Z = 1 (protons and other)	0.267(± 0.030)	135(± 15)	0.226
Z = 2 (^{3}He, ^{4}He)	$1.86(\pm 0.24)\cdot 10^{-2}$	135(± 15)	$2.30\cdot 10^{-2}$
Z = 3–5 (Li, Be, B)	$1.99(\pm 0.40)\cdot 10^{-4}$	175(± 25)	$3.31\cdot 10^{-4}$
Z = 6–8 (C, N, O)	$6.26(\pm 1.20)\cdot 10^{-4}$	250(± 25)	$1.31\cdot 10^{-3}$
Z = 9–13 (F to Al)	$1.10(\pm 0.20)\cdot 10^{-4}$	300(± 25)	$2.51\cdot 10^{-4}$
Z = 14–24 (Si to Cr)	$5.48(\pm 0.20)\cdot 10^{-5}$	400(± 25)	$1.53\cdot 10^{-4}$
Z = ≥ 25 (Mn, Fe and higher)	$1.20(\pm 0.11)\cdot 10^{-5}$	550(± 25)	$5.54\cdot 10^{-5}$

- Measured differential particle fluxes



Highlights from *Guo et al. (2017), "Measurements of the neutral particle spectra on Mars by MSL/RAD from 2015-11-15 to 2016-01-15"*



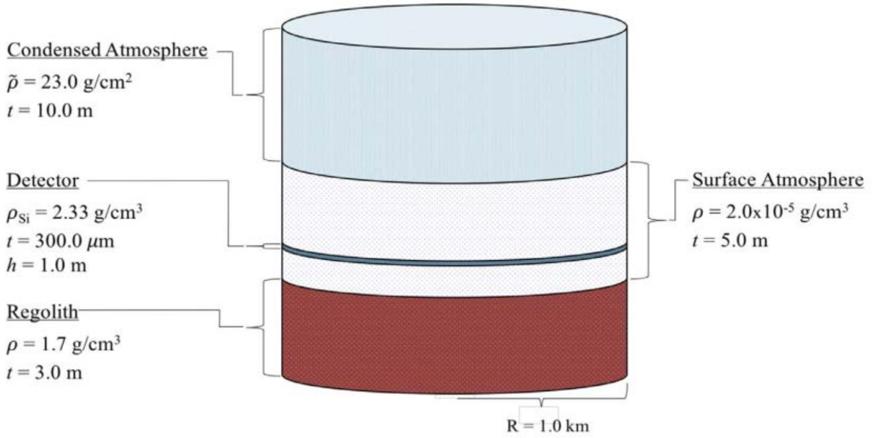
- Measured neutron and gamma spectra above ~7 MeV
- Dose rate from neutrons between 7 MeV and 740 MeV

Dose rate and dose equivalent rate of the inverted Martian neutron spectrum (7–740 MeV) from 2015-11-15 to 2016-01-15 .

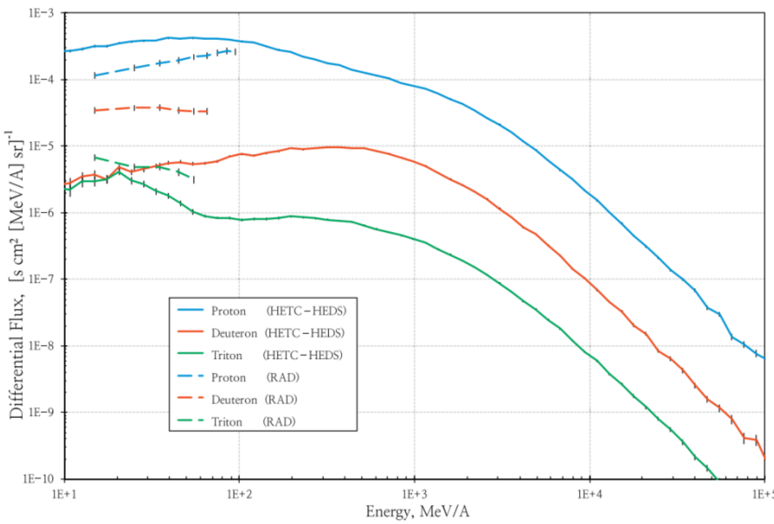
	Dose rate	Dose equivalent rate
Power law inversion	5.6 ± 0.8 μGy/d	25.3 ± 3.3 μSv/d
Full inversion	4.7 ± 0.9 μGy/d	22.0 ± 4.1 μSv/d
Averaged final	5.1 ± 1.0 μGy/d	23.6 ± 4.1 μSv/d
Mean total dose measured	233 ± 12 μGy/d	610 ± 45 μSv/d

Highlights from *de Wet & Townsend (2017), "A calculation of the radiation environment on the Martian surface"*

- Results from HETC-HEDS using a cylindrical geometry

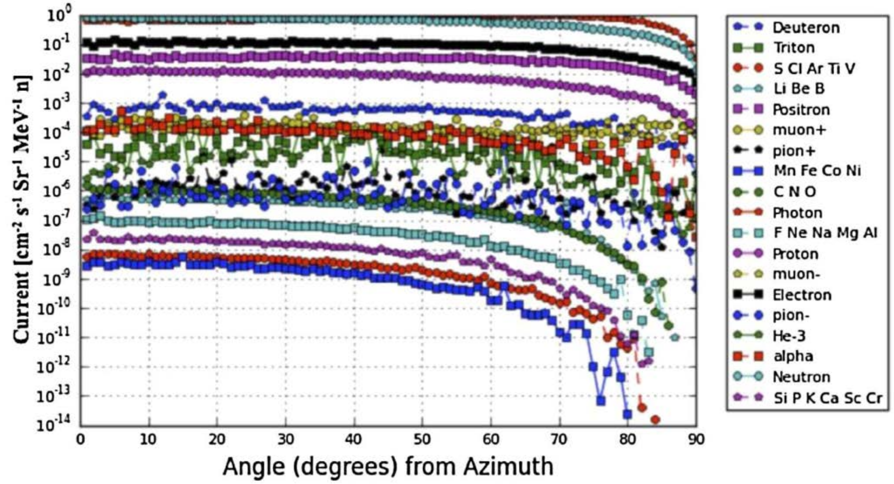


- Differential particle fluxes

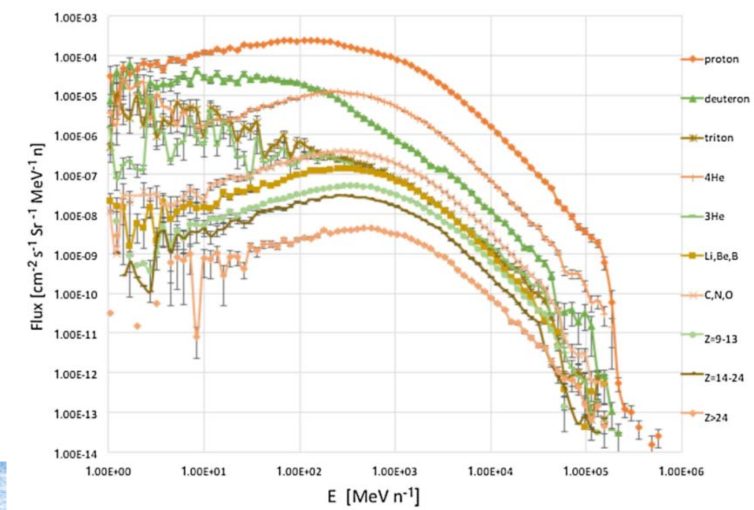


Highlights from *Flores-McLaughlin (2017), "Radiation transport simulation of the Martian GCR surface flux and dose estimation using spherical geometry in PHITS compared to MSL-RAD measurements"*

- Results from PHITS for a spherical geometry
- Zenith angle dependence

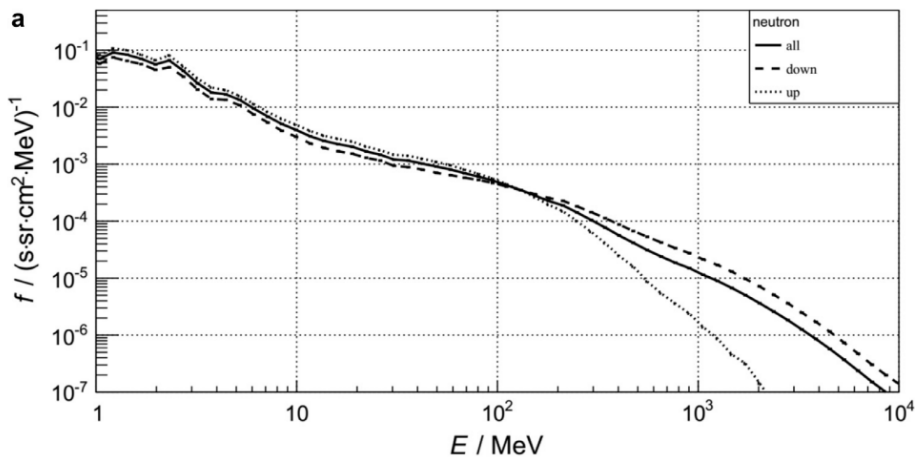


- Differential particle fluxes
- Dose rates

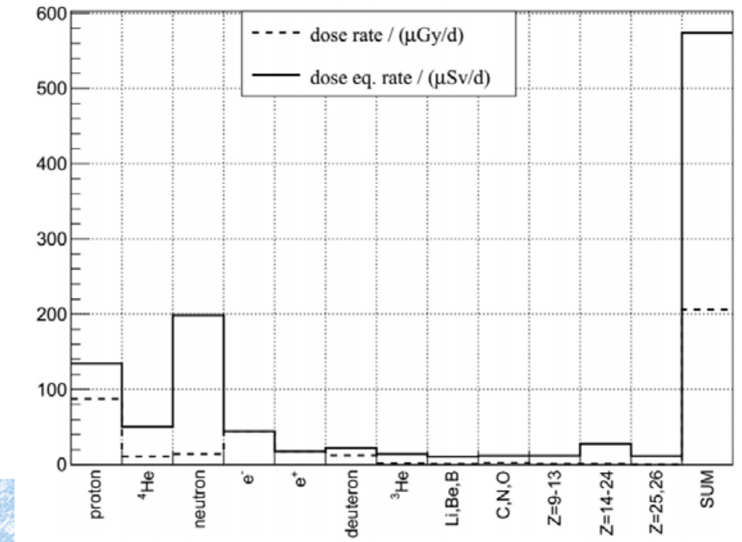


Highlights from
Matthiä & Berger (2017), "The radiation environment on the surface of Mars – Numerical calculations of the galactic component with GEANT4/PLANETOCOSMICS"

- Results from GEANT4 for a box geometry
- Differential particle fluxes
- Analysis of upward/downward flux



- Dose rates (per particle type)



Ratliff et al. (2017), “Simulation of the GCR spectrum in the Mars curiosity rover's RAD detector using MCNP6”

- Results from MCNP6
- Dose rates (per particle type)
- Differential particle fluxes

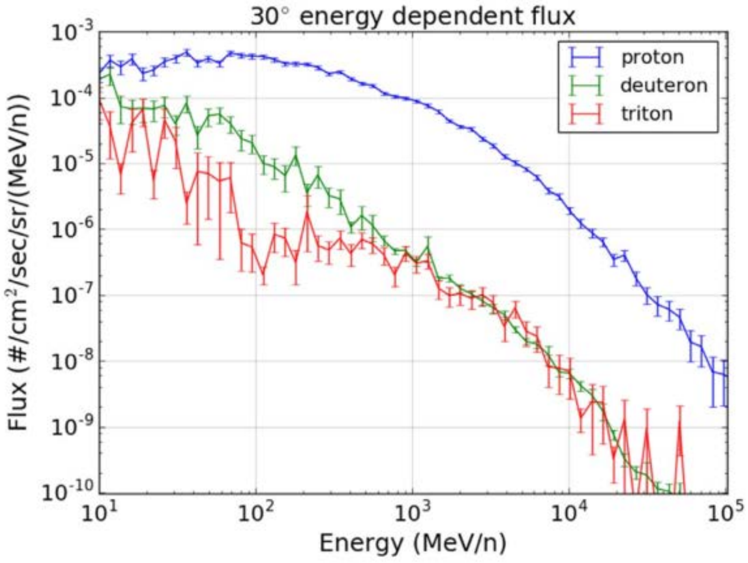
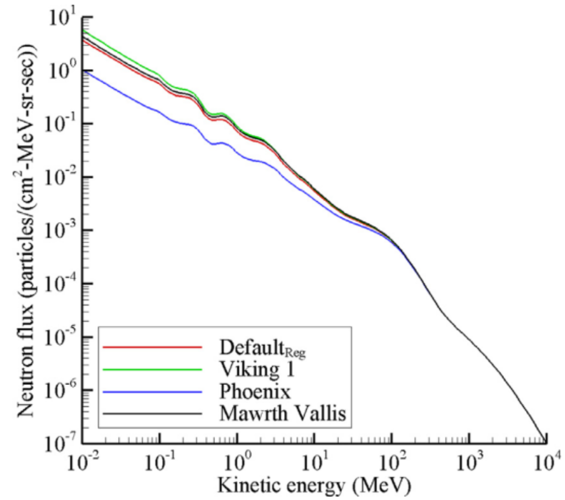


Table 2
Tabulated dose (D) and dose equivalent (H) values for 4π calculations.

Particle	$D_{4\pi}\left(\frac{\mu Gy}{day}\right)$	$H_{4\pi}\left(\frac{\mu Sv}{day}\right)$
Hydrogen	200.00 ± 0.52%	200.00 ± 0.52%
Deuteron	11.13 ± 2.39%	11.18 ± 2.39%
Triton	2.52 ± 4.41%	2.86 ± 4.27%
^{4}He	15.34 ± 0.98%	40.78 ± 2.32%
^{3}He	3.59 ± 3.56%	15.58 ± 4.31%
Li, Be, B	2.06 ± 2.13%	19.04 ± 4.70%
C, N, O	5.52 ± 1.29%	25.19 ± 2.97%
Z = 9–13	2.18 ± 1.24%	23.89 ± 1.71%
Z = 14–24	1.83 ± 1.17%	37.48 ± 1.14%
Z = 25–28	0.69 ± 2.64%	4.11 ± 2.51%
N	0.0642 ± 92.64%*	0.3240 ± 91.68%*
Γ	2.65 ± 20.09%	2.65 ± 20.09%
e^-	2.64 ± 5.49%	15.15 ± 2.84%
e^+	1.69 ± 6.69%	9.44 ± 8.42%
μ^-	15.16 ± 1.66%	15.16 ± 1.66%
μ^+	18.36 ± 1.47%	18.36 ± 1.47%
π^-	10.15 ± 1.83%	10.15 ± 1.83%
π^+	11.69 ± 1.70%	11.69 ± 1.70%
Total	307.34 ± 0.43%	473.13 ± 0.51%

Slaba & Stoffle (2017), “Evaluation of HZETRN on the Martian surface: Sensitivity tests and model results”



- Results from HZETRN
- Influence of regolith composition

Table 3
Integrated exposure quantities on the Martian surface using regolith definitions from Table 1.

Regolith definition	Dose in tissue (mGy/day)	Dose equivalent (mSv/day)	[a]Neutron effective dose (mSv/day)
Default$_{Reg}$	0.172	0.539	0.163
Viking 1	0.174	0.579	0.176
Phoenix	0.167	0.452	0.124
Mawrth Vallis	0.173	0.563	0.174

[a] The neutron effective dose column was obtained by folding the neutron spectra from Fig. 2 with isotropic neutron fluence to effective dose conversion coefficients from Pelliccioni (2000).

- Influence of atmospheric composition
- Comparison of BON2014 and DLR2013 model

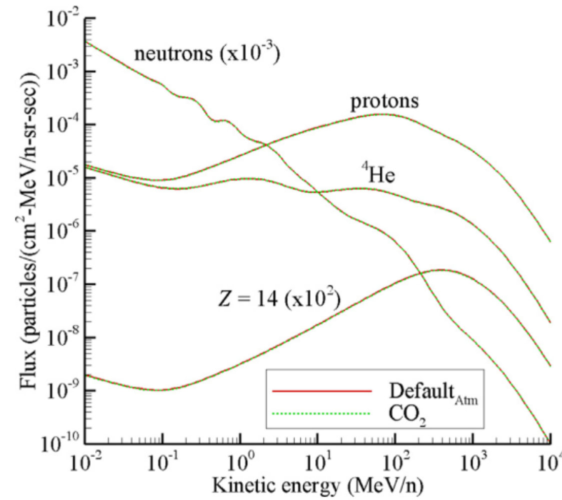


Fig. 3. Charged particle fluxes on the Martian surface using the atmosphere definitions from Table 2. The neutron and $Z = 14$ flux results have been scaled by 10^{-3} and 10^2, respectively, to improve plot clarity.

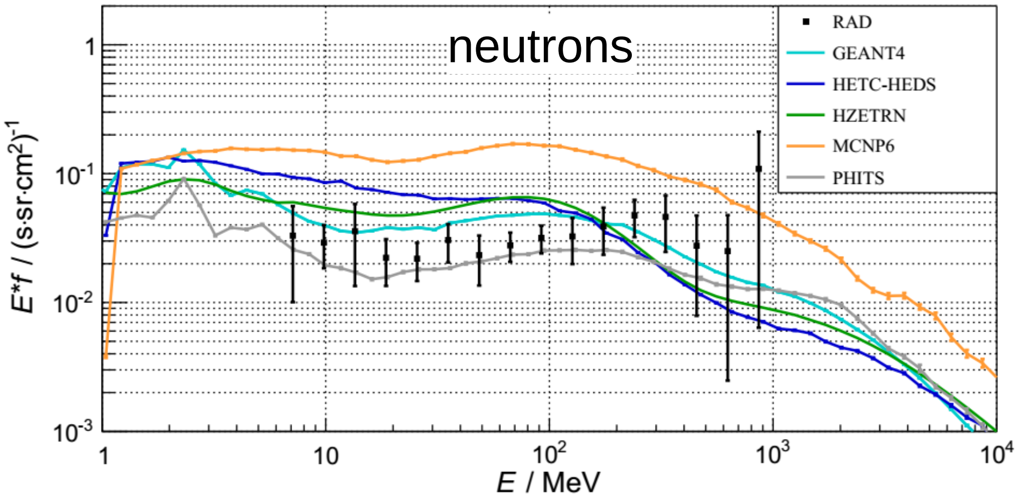
Table 4
Integrated exposure quantities on the Martian surface using the BON2014 and DLR2013 GCR models.

GCR model	Dose in tissue (mGy/day)	Dose equivalent (mSv/day)
BON2014	0.172	0.539
DLR2013	0.177	0.560

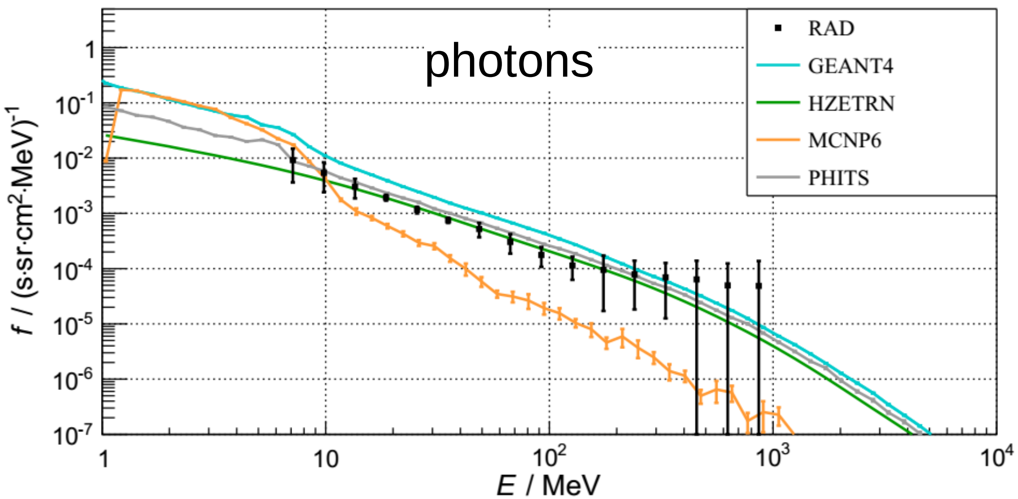
Summary paper, neutral particles

Matthiä et al. The radiation environment on the surface of Mars - Summary of model calculations and comparison to RAD data. *LSSR,* in press 2017

- **Neutrons:**
- differences of one order of magnitude (PHITS,HETC-HEDS,MCNP6)



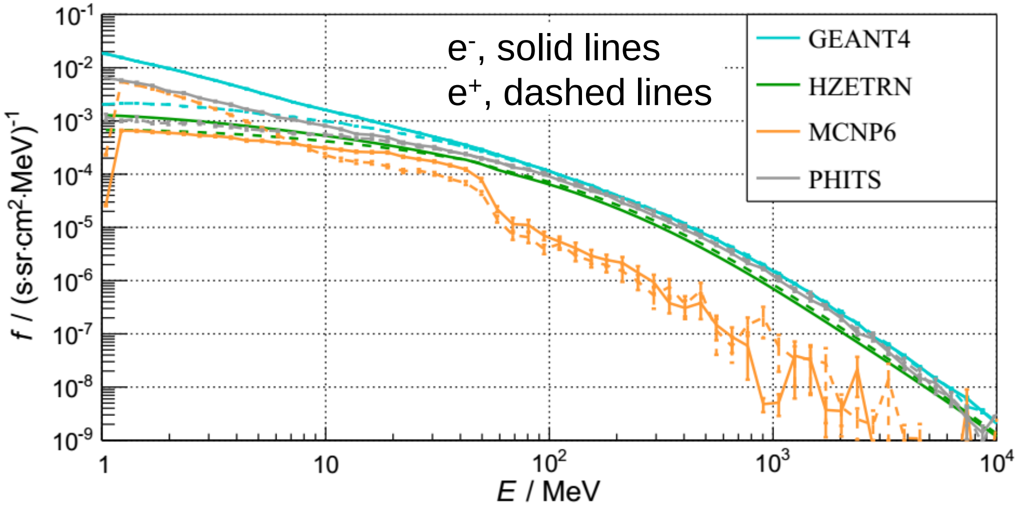
- **Photons:** large underestimation of MCNP6 – π^0 transport not simulated → Underestimation of the electromagnetic cascade



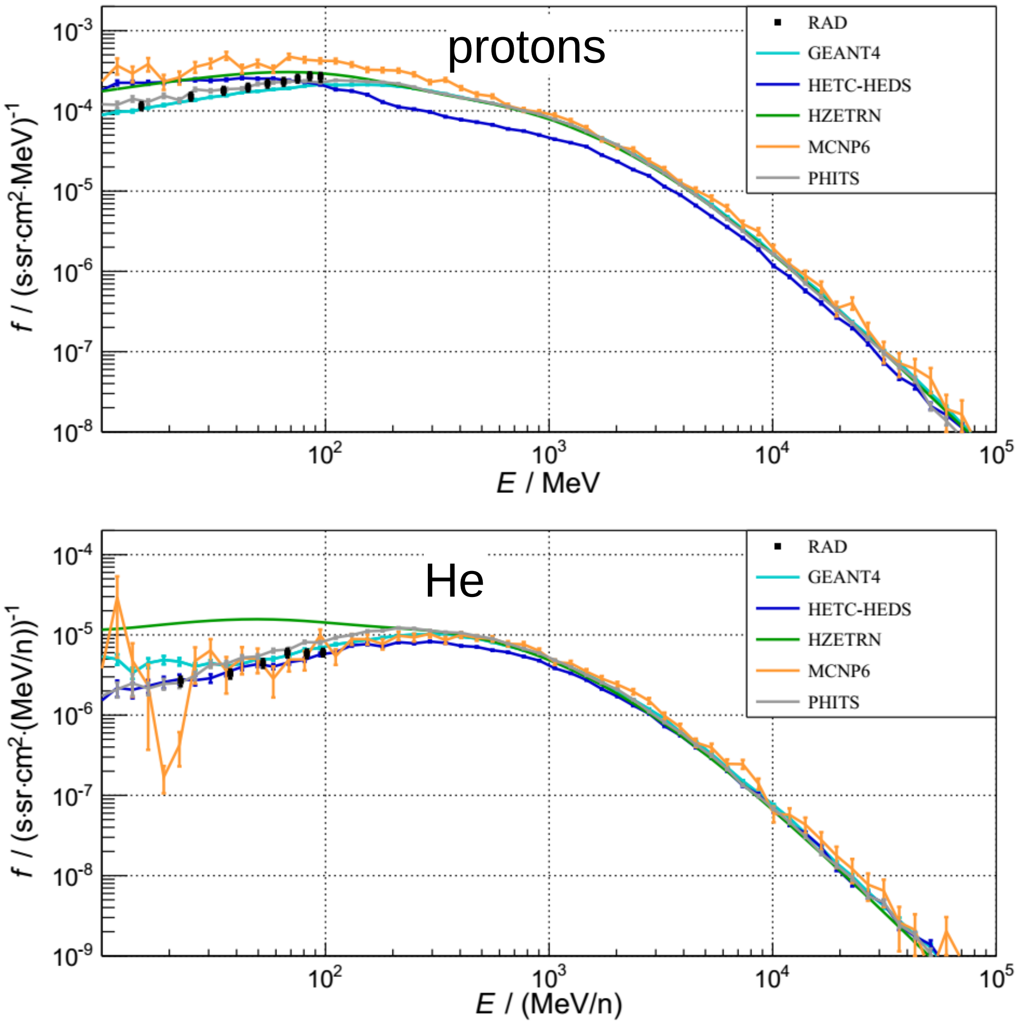
Summary paper, electron/positron

- large underestimation of MCNP6 – π^0 transport not simulated → Underestimation of the electromagnetic cascade
- Order of magnitude differences at E<10MeV

Matthiä et al. The radiation environment on the surface of Mars - Summary of model calculations and comparison to RAD data. *LSSR*, in press 2017

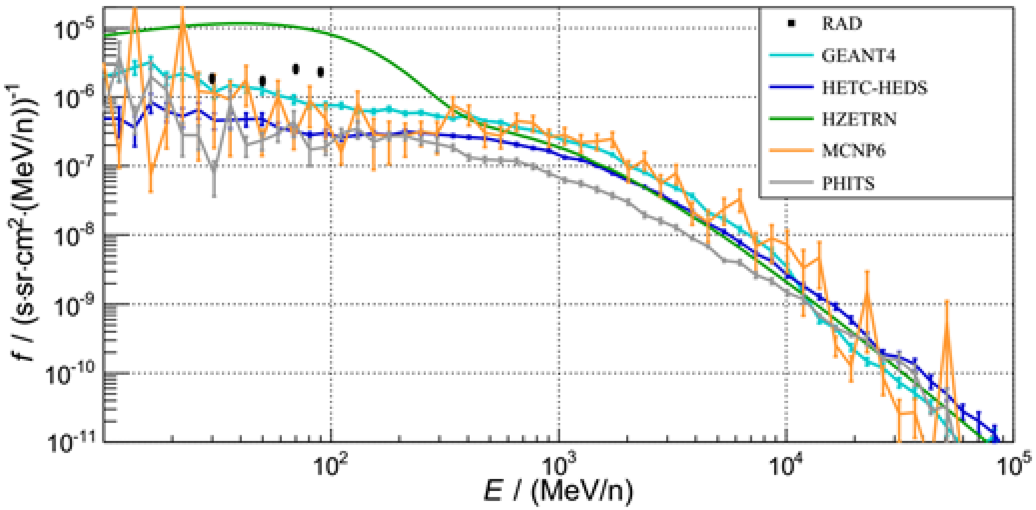


Summary paper, protons and He

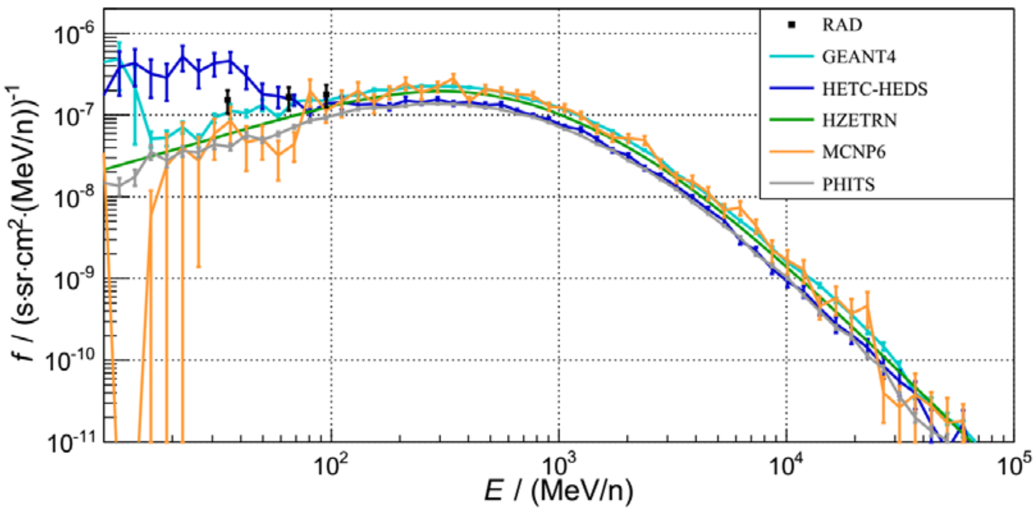


Matthiä et al. The radiation environment on the surface of Mars - Summary of model calculations and comparison to RAD data. *LSSR,* in press 2017

^{3}He and Li,Be,B

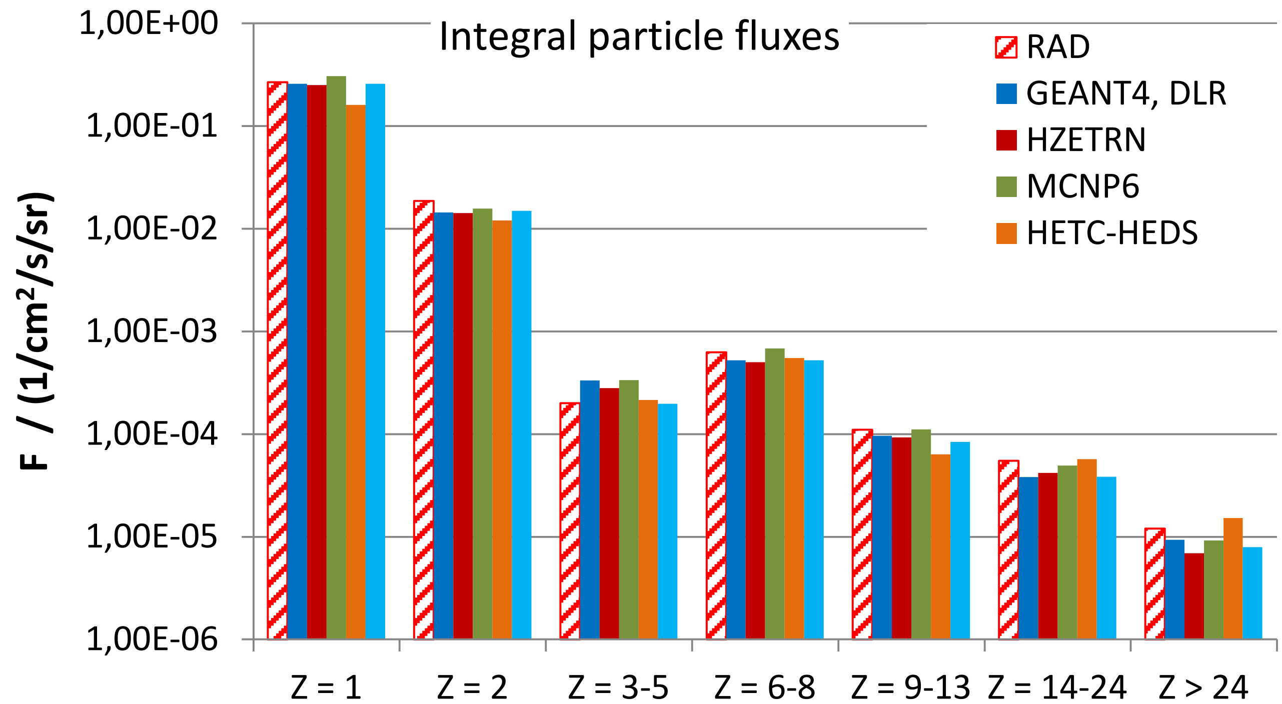


^{3}He



Li,Be,B

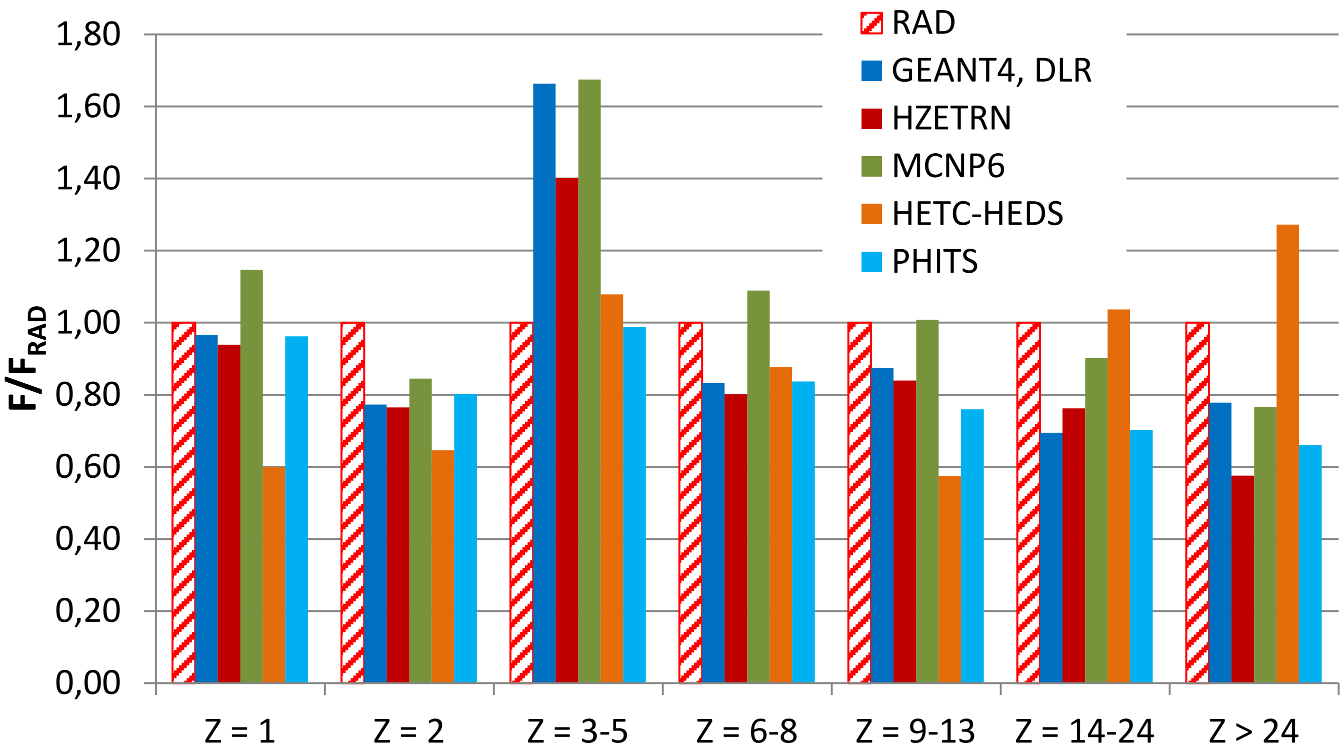
Integral particle fluxes



- Lower energy thresholds:

Z	1	2	3-5	6-8	9-13	14-24	>24
E / (MeV/n)	120	120	150	225	275	375	525

Integral particle fluxes, ratio to RAD

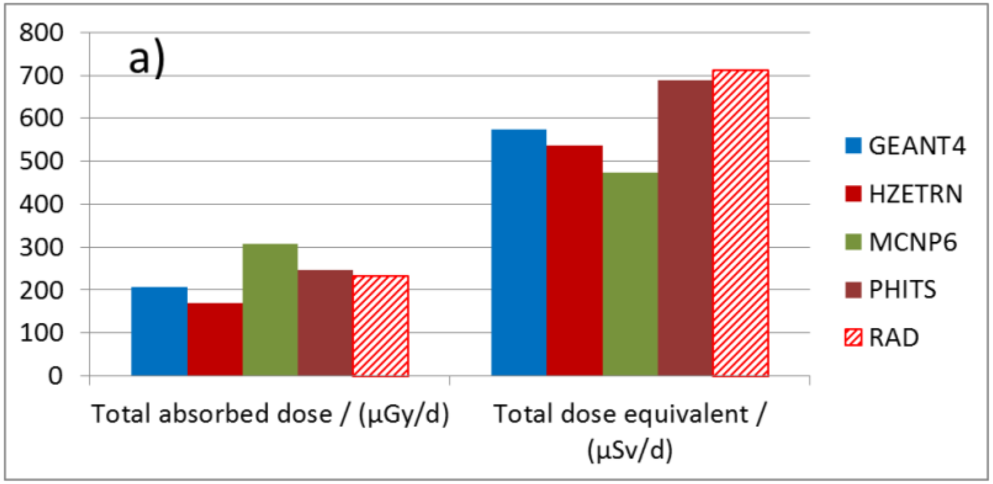


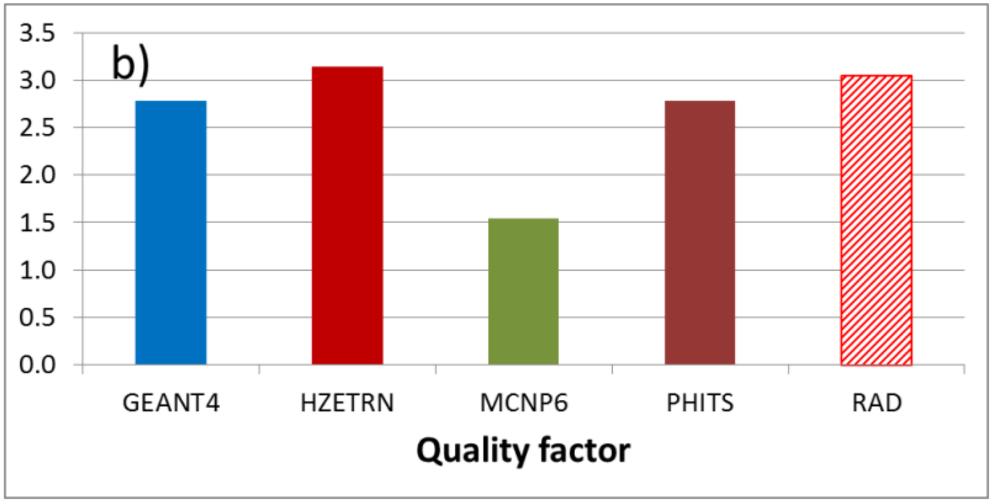
- Mostly between 70% and 130% of RAD
- Tendency to under-predict *Z*=2, *Z*≥6

Dose rates and quality factor

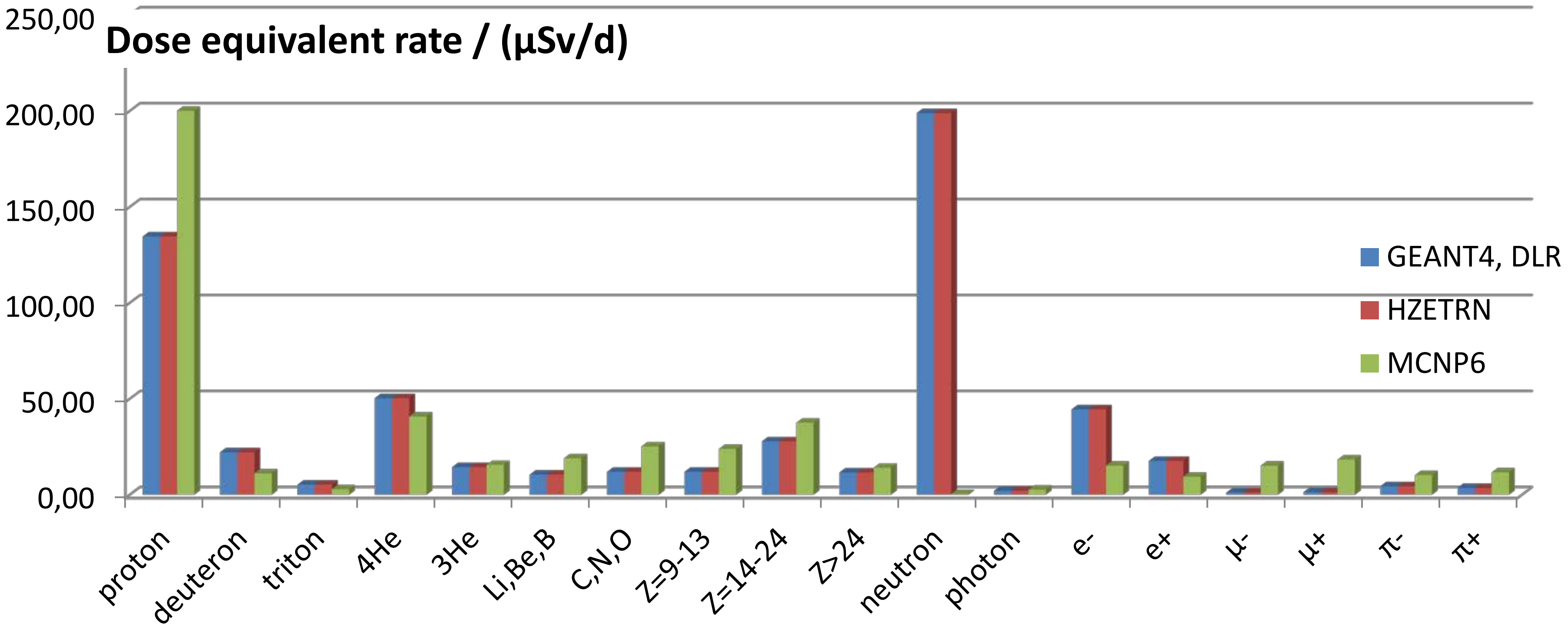
Matthiä et al. The radiation environment on the surface of Mars - Summary of model calculations and comparison to RAD data. *LSSR*, in press 2017

- No dose rates from HETC-HEDS
- Absorbed dose rates
    - Models: 0.17-0.31 mGy/d
    - RAD: 0.23 mGy/d
- Dose equivalent rates
    - Models: 0.47-0.69 mGy/d
    - RAD: 0.71 mSv/d
- Quality factor
    - Models: 1.5-3.1
    - RAD: 3.05





Dose rates- particle per particle



- Neutrons and protons contribute with more than 50%
- MCNP6: no neutron dose, energy deposition through secondary protons
- MCNP6: low e+,-, high µ, π;

Comparison of calculated and measured dose rates

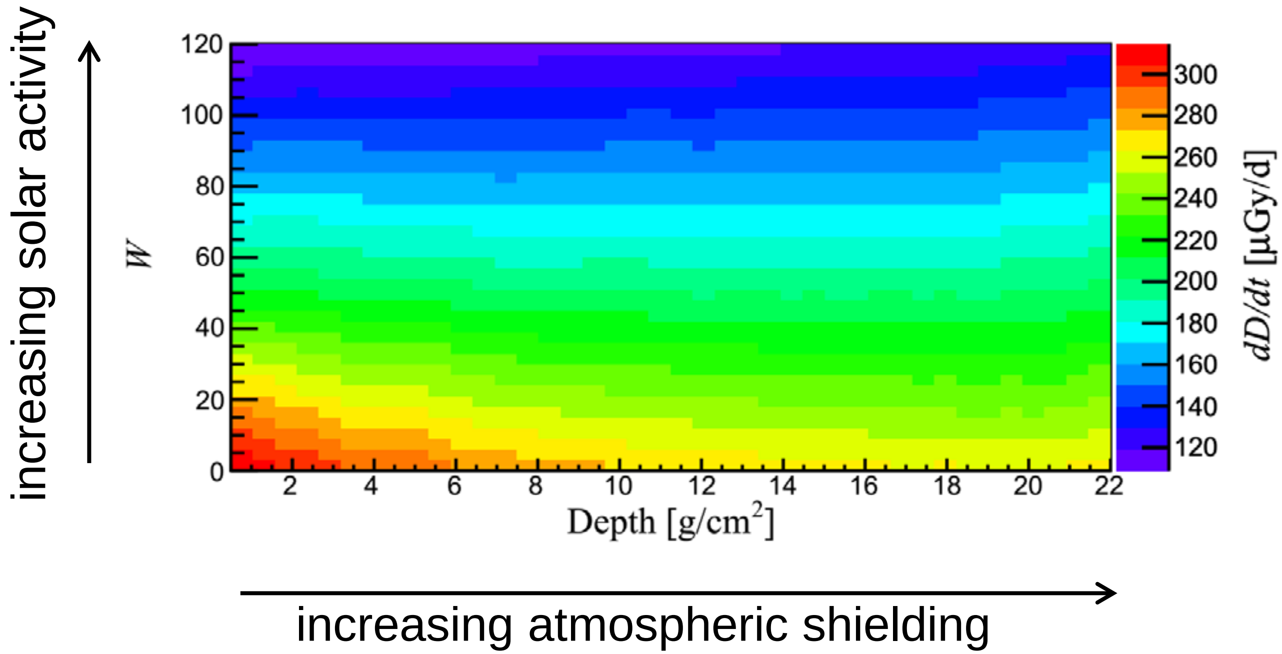
black: first comparison, first 200 sol on Mars
red: workshop results: 15 Nov 2015 - 15 Jan 2016

NOTE: Values in black parenthesis are the derived quality factors for a restricted zenith angle θ<30°.

	MSL-RAD	GEANT4	PHITS	OLTARIS2013	HZETRN/ OLTARIS	MCNP6
absorbed dose rate [mGy/d]	0.21±0.04 0.23±0.01 (+10%)	0.19 0.21 (+11%)	0.20 0.25 (+25%)	0.16	0.18 0.17 (-6%)	0.31*
dose equivalent rate [mSv/d]	0.64±0.12 0.61±0.12 (-5%)	0.52 0.57 (+10%)	0.60 0.69 (+15%)	0.52	0.54 0.54 (±0%)	0.47*
Quality factor	3.05±0.26 2.62±0.14 (-14%)	2.7 2.8	3.0 2.8	3.2	3.0 3.1	1.5*

*revised values in Ratliff et al. (2017): 370 µGy/, 996 µSv/d, Q=2.7

3. Development of a parameterized radiation model for the Martian atmosphere



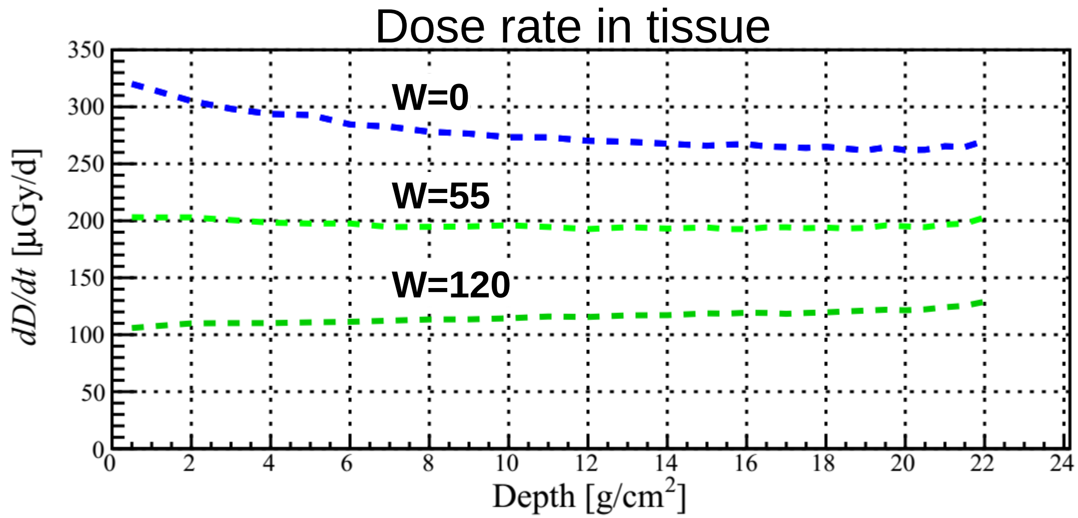
Based on pre-calculated tables for GCR primaries parameterized in solar activity and atmospheric shielding

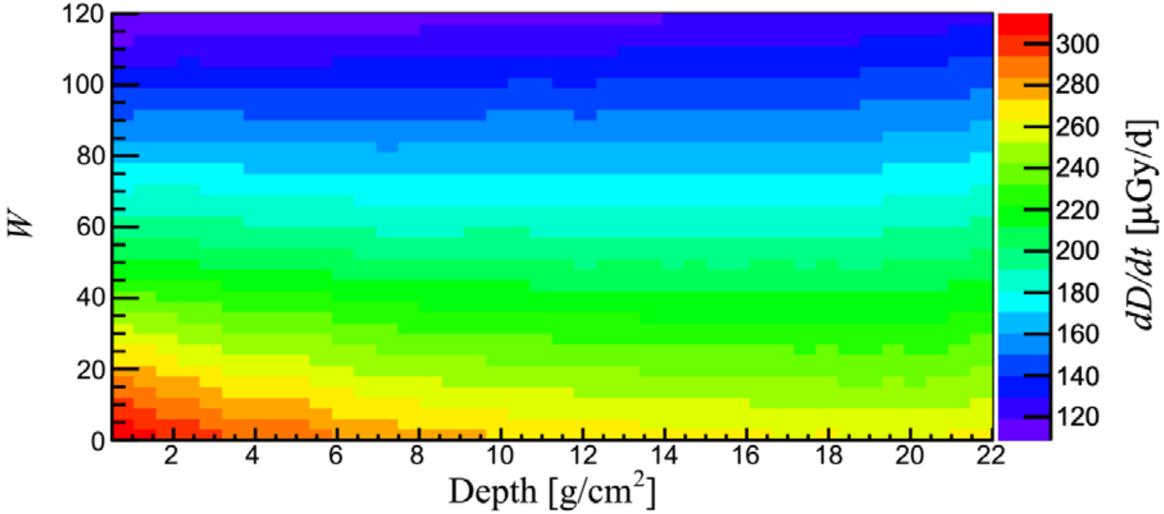
Development of a parameterized radiation model

- Calculate dose rate vs depth for GCR (Z=1-28) for 3 solar modulations (low, medium and high activity)
- Calculate dose rate vs depth for GCR (H, He) for several solar modulation
- Use ratio to scale the result of GCR (H, He)
- Dose rate in Si, dose rate in tissue, dose equivalent rate

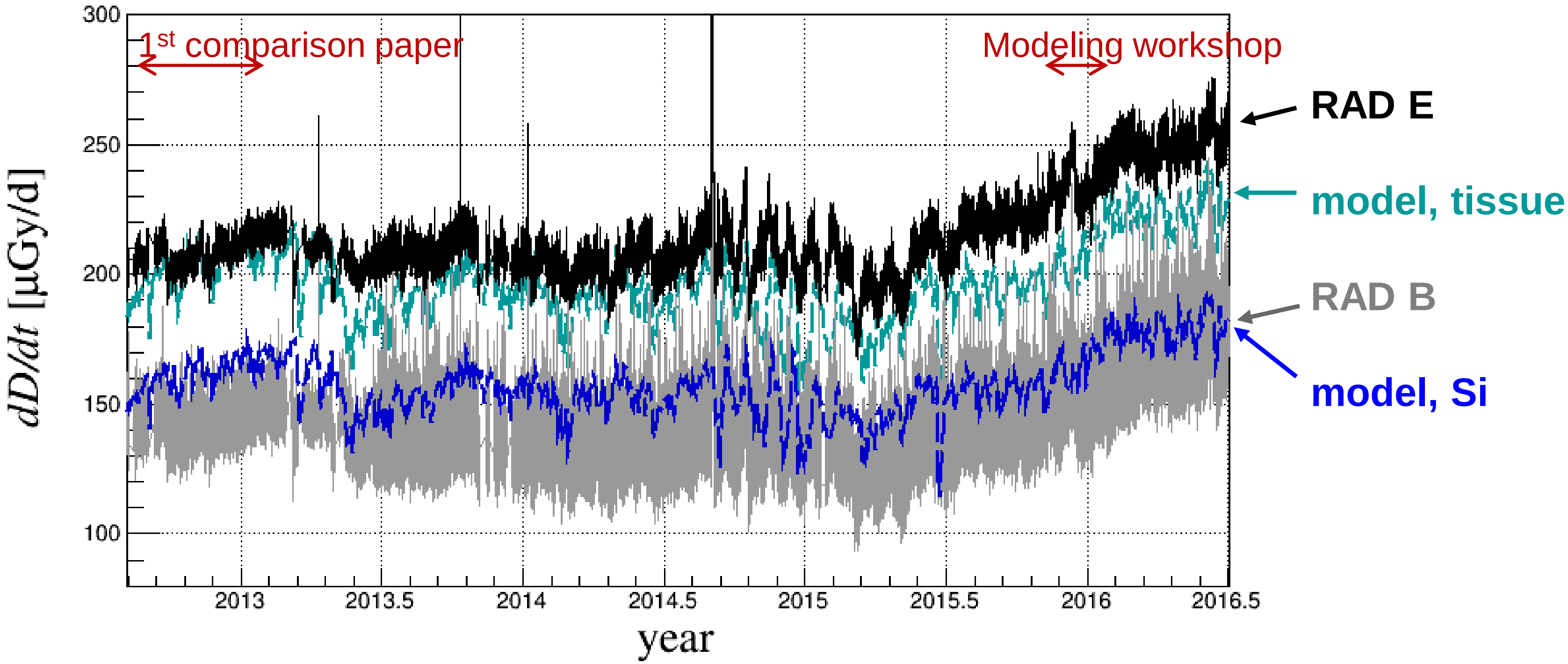
Development of a parameterized radiation model

- decrease of dose rates with depth (low solar activity)
- constant dose rates with depth (higher solar activity)
- surface effect – increase of dose rates



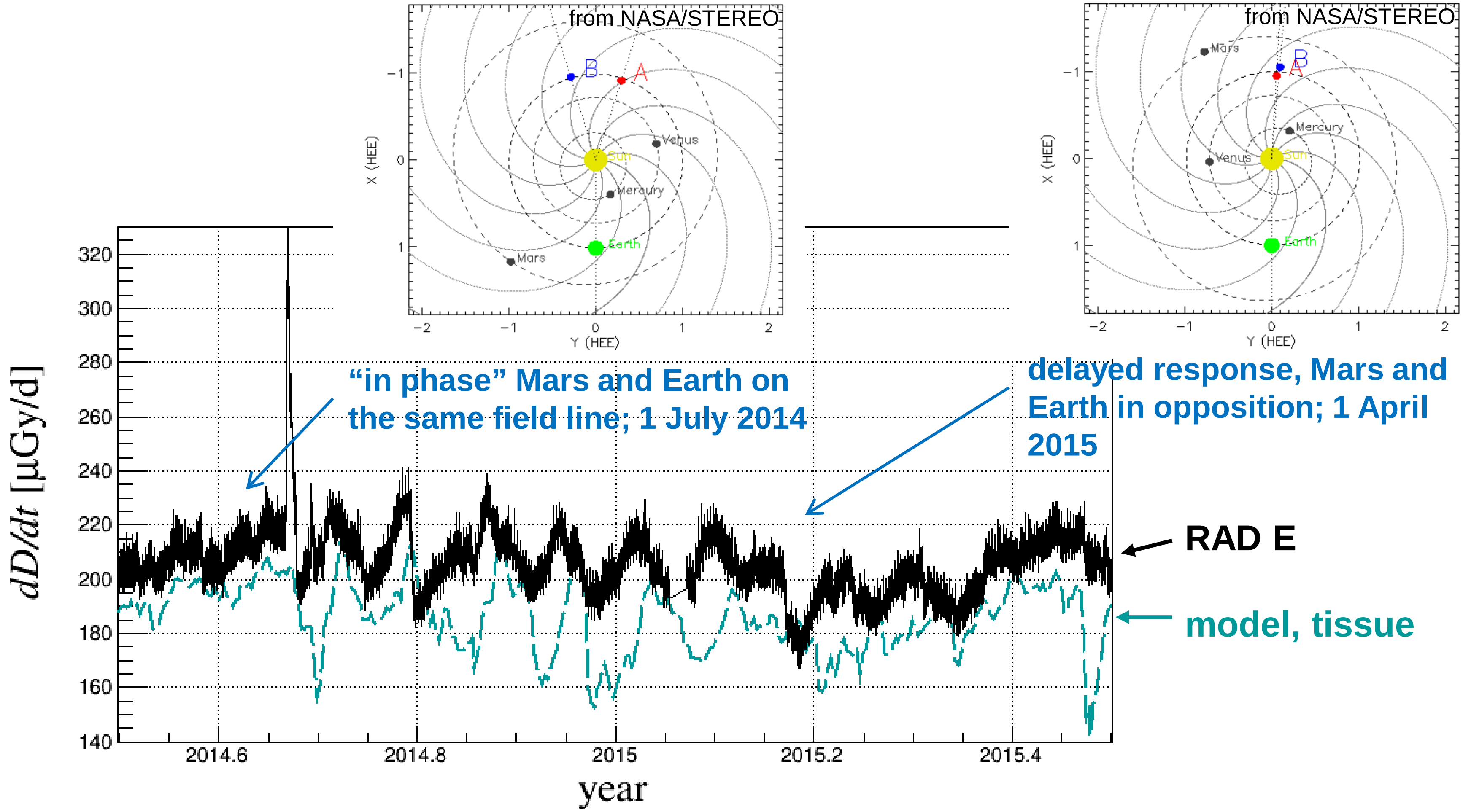


Development of a parameterized radiation model Dose rate at the Martian surface (22 g/cm²)



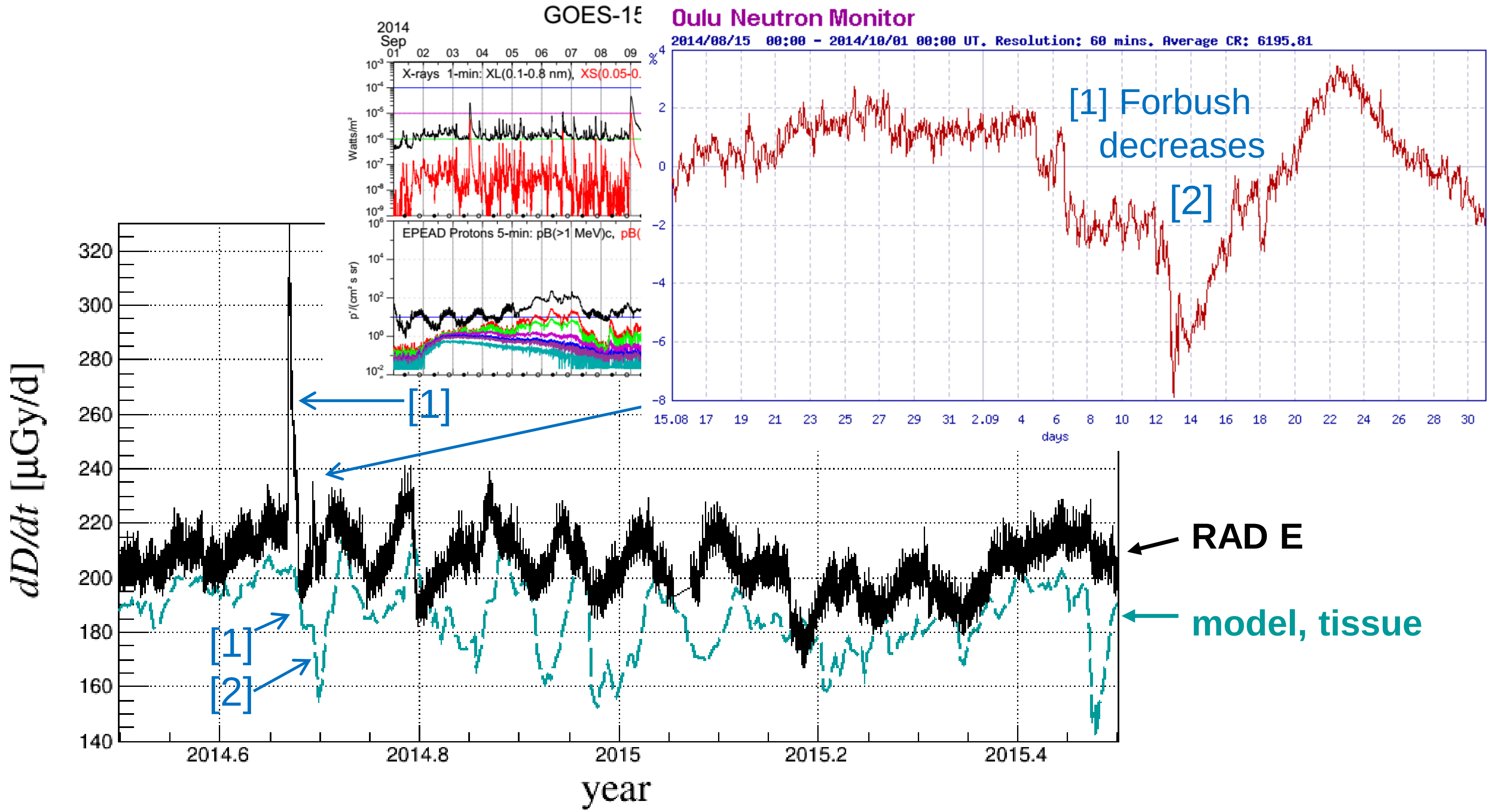
- GCR intensity based on Neutron Monitor data!

Dose rate at the Martian surface (22 g/cm²): 2014/2015



- GCR intensity based on Neutron Monitor data!

Dose rate at the Martian surface (22 g/cm²): 2014/2015



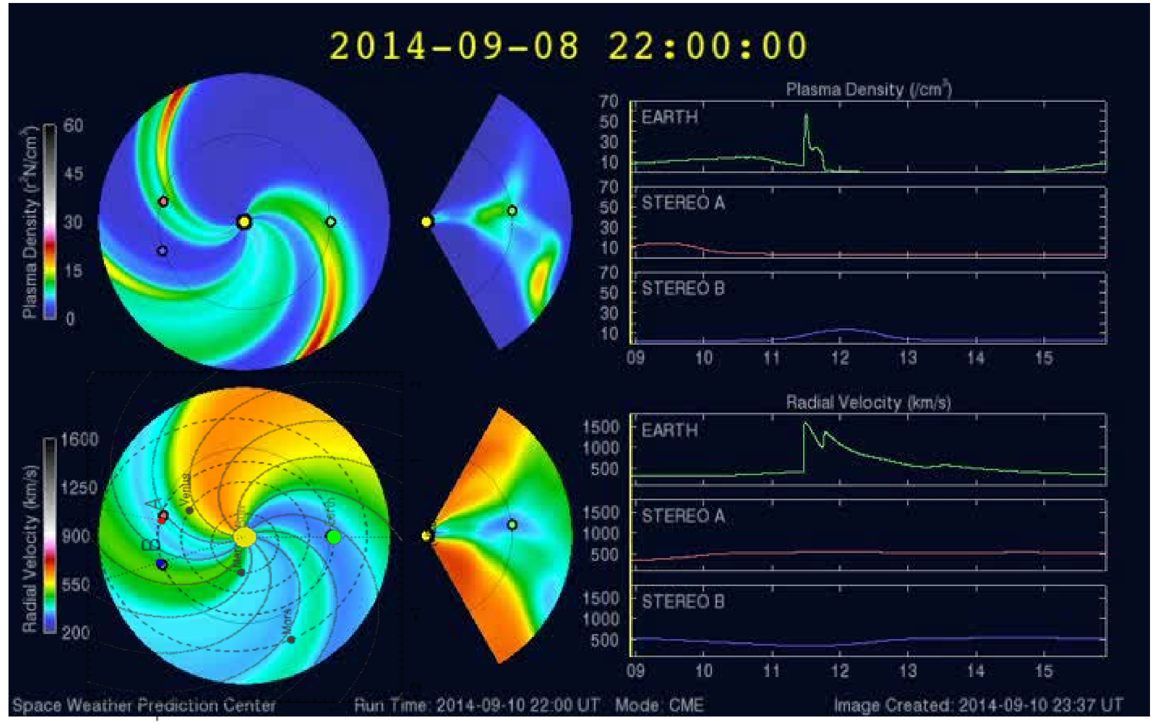
[1] 1 Sept 2014, large on Mars, small at Earth
[2] 10 Sept 2014, small on Mars, large at Earth

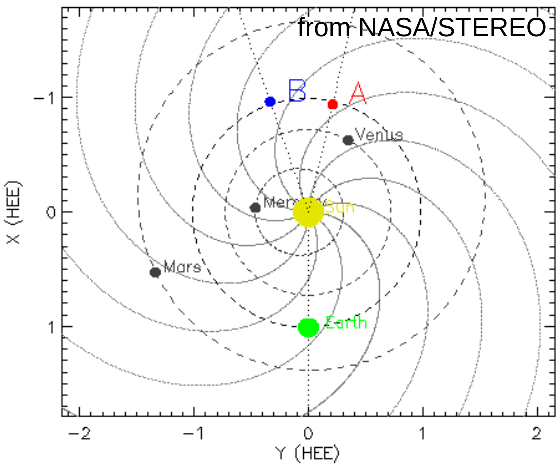
SEP on 10 Sep 2014, flare at N16W06

Enlil model
https://ccmc.gsfc.nasa.gov
https://www.ngdc.noaa.gov/enlil/

Solar wind density

Solar wind velocity





Energy spectrum and connection of Mars to the event/CME are likely causes for the low response measured by MSL

Summary

- Output of DLR and BO-10/BO-14 model similar (<5%); differences in dose rates ≤ 5%
- Reasonable agreement between different transport models for many particles but severe differences for others
- Calculated total dose rates are compatible with measurements, but in some cases large discrepancies in the contribution of individual particle types

- Promising results for the parameterized model for dose rate in Si and tissue (long term trends)
- Short term behavior not nicely reproduced – What could be used instead of NM data for the primary GCR intensity…?

Future work

- Continue model inter-comparison and validation applying the detector geometry
- Investigate possibilities to describe the primary GCR intensity at Mars to model the short term variations
- Investigate the discrepancies starting at around July 2015 between the parameterized model and RAD E dose rate
- Implementation of organ dose rates and solar particle events in the surface model