ARAMIS : A model of Martian surface radiative environment

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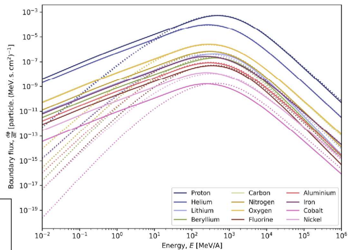
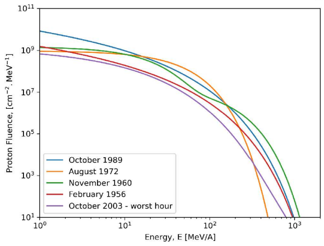
Space Radiation Environment

Galactic Cosmic Rays (GCR) :

- Originated from outside the solar system and anti-modulated with solar cycle
- Fully charged atomic nuclei (^{1}H to ^{238}U) with 87% Protons, 12% He, ~1% Z>2
- Extremely high energy and very penetrating (difficult to shield)

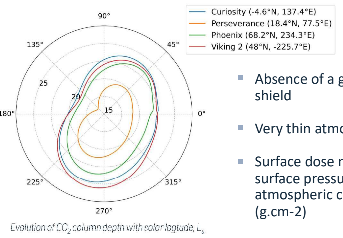




Solar Particle Events (SPEs):

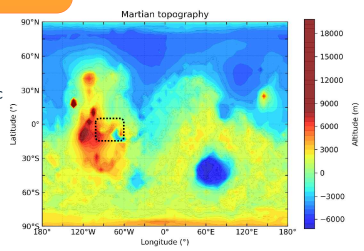
- Sporadic and directional events with highest probability at solar maximum
- Mostly low energetic proton (< 1 GeV)
- Alert time ~20 minutes

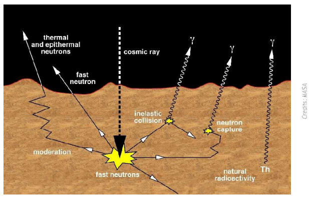
Martian atmosphere specificities



Evolution of CO_2 column depth with solar logitude, L_s

- Absence of a global magnetic shield
- Very thin atmosphere
- Surface dose modulated by surface pressure (Pa) or atmospheric column depth (g.cm-2)





Secondary particle generation :

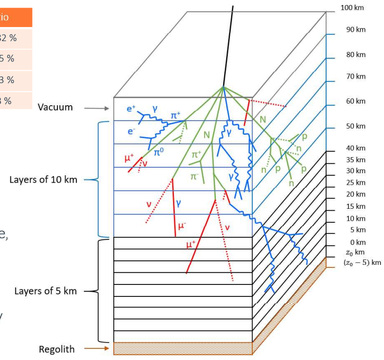
- All types of particle : neutrons, electrons, photons, muons, different ion isotopes, …
- Atmospheric shower phenomenon : billions of secondary particles created by interaction with the atmosphere
- Albedo creation : nuclear interaction between the planetary surface and GCR generating mainly neutrons and photons

ARAMIS architecture and GEANT4 Geometry

Regolith Defaults composition	Ratio
SiO_2	51.2 %
$Al_2CaK_2MgNa_2O_7$	32.1 %
FeO_3	9.3 %
H_2O	7.4 %

Atmosphere elements	Ratio
CO_2	95.482 %
N_2	2.705 %
Ar	1.603 %
O_2	0.13 %

- Thermodynamic parameters of the atmosphere imported from the Mars Climate Database (MCD v6.1)
- Parametric atmosphere geometry to suit any landing site regarding altitude and position (latitude, longitude)
- Higher number of near-surface layers
- Used with every primary ion up to Z=28 and every secondary (charged or neutral particles)



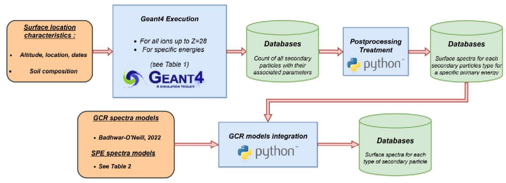
ARAMIS : Atmospheric RAdiation Model for Ionizing spectra on martian Surface

- Geant4 v11.1.0 (C++) & Python codes ran with the CNES High Performance Computing (HPC) cluster
- Physic lists : *FTFP_INCLXX_HP*
- Convolution of surface response function with primary spectra :

$$\left.\frac{d\phi_j}{dT^*}\right|_{z_0} = 2\pi \sum_i \int_T \frac{dN_{ij}}{dT^*}(T, z_0) \cdot \frac{d\phi_i}{dT} dT$$

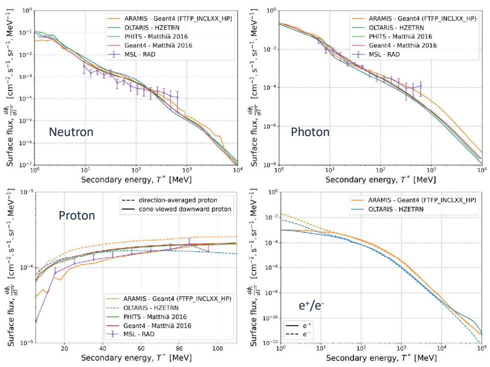
- Relative error calculated per bin :

$$R_{kj} = \left[\frac{\sum_{p=1}^{N} T_p^{*2}}{\left(\sum_{p=1}^{N} T_p^*\right)^2} - \frac{1}{N}\right]^{1/2}$$



Primary parameters	GCRs	SPEs
Energy	100 MeV 500 MeV 1 GeV 5 GeV 10 GeV 50 GeV 100 GeV 500 GeV 1 TeV	100 MeV 150 MeV 200 MeV 250 MeV 300 MeV 350 MeV 400 MeV 450 MeV 500 MeV 1 GeV 5 GeV
Particle type	All ions up to Z=28	Proton

Results validation with MSL-RAD measurements



Martian surface flux of neutron, photon, proton and e+/e- on Gale Crater from 19 August 2012 to 17 February 2013, given by ARAMIS and compared to measurements and other models with FTFP_INCLXX_HP.

GCR induced spectra :

- Much wider range of energy (from 10^{-3} to 10^5 MeV) and flux for neutron, photon, electron, proton, alpha, all isotopes up to Z=28 , …
- ARAMIS present the best fit with the MSL Curiosity rover's measurements for protons on the all spectrum and for neutral particles at high energies (E>100 MeV) better than other existing models
- ARAMIS allows the distinction in the fluxes between Albedo particles and secondary particles created with atmospheric showers but also with particle incoming an opening angle (i.e. protons with RAD) [1]
- Photons are mostly generated by nuclear reactions between cosmic particles and regolith, while electrons are generated by nuclear reactions between cosmic particles and atmosphere and neutron's origins are equilibrated

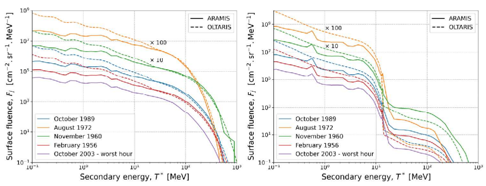
SPE induced spectra :

- ARAMIS presents an atmospheric cut-off for protons about 160 MeV [1]
- A comparison between OLTARIS/ ARAMIS and the method from [2] defining the pivot energy as a function of surface pressure :

$$D_{surf}(p)\ [mGy] = c_D(p) \cdot F_{E_0}(p)$$

$$\begin{cases} E_0(p) = -0.000114 \cdot p^2 + 0.350 \cdot p + 86.9 \\ \frac{c_D(p)}{10^{-7}} = -0.000614 \cdot p^2 + 1.08 \cdot p + 388 \end{cases}$$

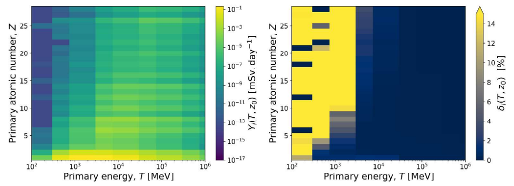
- ARAMIS and OLTARIS show good agreement with pivot method surface dose
- For combinations of events, the pivot method is therefore not the most appropriate, although it provides extremely accurate results for other spectral shapes.



Martian surface fluence of neutrons (left) and photons (right) on Gale Crater from 19 August 2012 to 17 February 2013 for different SPE historical events

Events	Models mean absorbed dose [mGy]				Pivot method absorbed dose [mGy]	
	ARAMIS		OLTARIS		Zhang et al. (2023)	Guo et al. (2019b)
	Male	Female	Male	Female		
February 1956	3.8	3.88	3.8	3.87	4.34	5.1
November 1960	21.54	21.99	23.33	23.74	33.81	39.4
August 1972	4.87	4.94	6.72	6.84	2.28	2.75
October 1989	12.04	12.28	11.85	12.07	12.53	14.74
October 2003 worst hour	0.67	0.68	/	/	0.6	0.66

Dosimetric tools

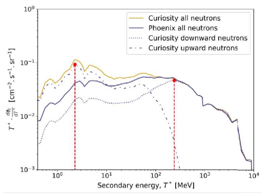


$$\begin{cases} Y_i(T, z_0) = \sum_j \int_{T^*} F_{ij}(T, T^*, z_0) C_j(T^*) dT^* \\ F_{ij}(T, T^*, z_0) = 2\pi \left[\frac{dN_{ij}}{dT^*}(T, T^*, z_0) \cdot \frac{d\phi_i}{dT}\right] \end{cases}$$

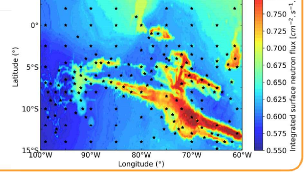
$$\delta_i(T, z_0) = \frac{\left[\sum_j \sum_k (F_{kj} R_{kj})^2 C_j(T^*)^2\right]^{1/2}}{Y_i(T, z_0)}$$

- The effective dose rate yield function, $Y_i(T, z_0)$ allows to identify the most contributing species and energies to the surface dose : GCR hydrogen and helium ions between 1 and 10 GeV represent the main contributor
- Monte Carlo uncertainty propagation in yield calculation is large (>14%) at low energies for all species where yield is minimal, which does not influence its value

Radiation cartography



- Neutrons show two peaks in the spectrum, at 2.3 MeV and 240 MeV, corresponding to neutrons evaporating from excited nuclei and neutrons created by spallation processes between primary and atmospheric nuclei
- Downward particles shape the high-energy flow, while upward particles shape the low-energy spectrum



- Improved Shepard interpolation method, addressing screening and "bull's eye" effects (considers relative position of data points and desired slopes)
- Smooth results for neutrons in Valles Marineris for interpolation with surface pressure

[1] Charpentier G., Ruffenach M., Benacquista R., Ecoffet R., Dossat C., et al. (2024). ARAMIS: a Martian radiative environment model built from GEANT4 simulations. *Journal of Space Weather and Space Climate*
[2] Zhang, J., J. Guo, and M. I. Dobynde, 2023. What Is the Radiation Impact of Extreme Solar Energetic Particle Events on Mars? Space Weather, 21(6)

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