

Microdosimetry and Dose equivalent for astronauts

High Performance Monte Carlo
Radiation Simulations workshop

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Characteristics

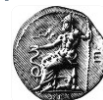
- i. Space radiation (SR) is primarily chronic and low dose ($\sim 1\text{-}2\text{mSv/day}$)
- ii. SR consists of Van Allen (VA) belts, Solar Particle Events (SPEs) and Galactic Cosmic Rays (GCRs)

Impact on Beyond LEO missions (Moon, Mars)

- i. SR is currently considered a mission-limiting factor
- ii. Of most concern are SR-induced long-term biological effects, such as cancer induction and late reactions (e.g., cardiovascular disease, cognitive impairment)

Uncertainty

- i. There is a huge uncertainty in **cancer risk assessment**
- ii. Primarily due to the uncertainty ($\sim 300\%$) of the quality factor (Q)



Major challenges for space radiation protection:

1. **No space epidemiology** → Difficult to set dose/risk limits for planned BLEO missions (e.g., to the Moon and Mars)
2. **Limited experimental data** on radiation quality (Q) of space radiation → large deviations on the adopted Q values among space agencies

Main methods for estimating Q :

1. ICRP Publication 60 (based on $Q(LET)$ function)
2. NASA's models (based on $Q(Z^2/\beta^2)$ function)



DOSE/RISK LIMITS IN LEO

- Different dose limits and risk models for LEO missions by agencies:

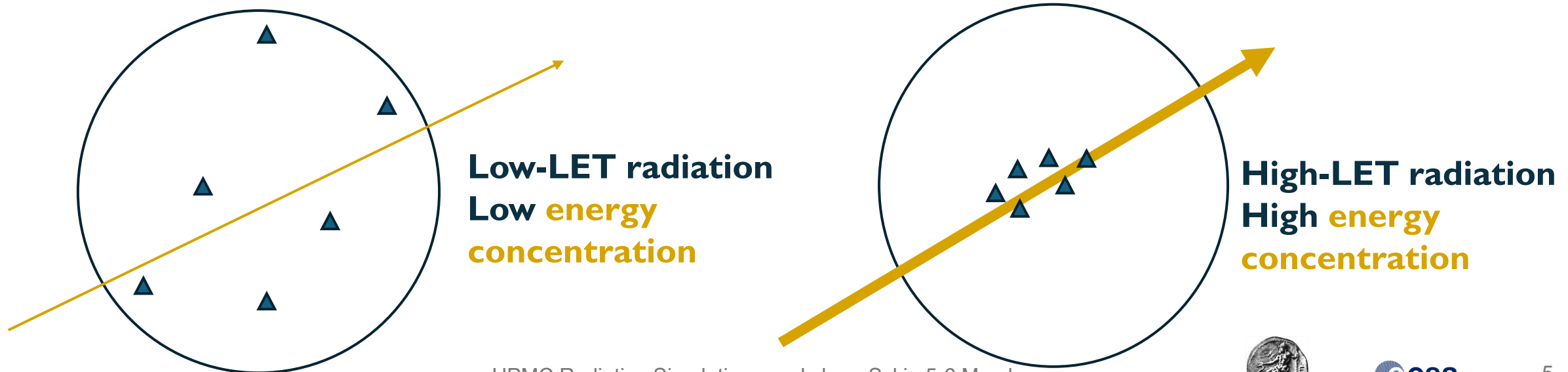
Agency	Effective Dose (Risk) limit	Risk model
NASA	600 <i>mSv</i> (3% fatal cancer)	NSCR 2012 (used)
ESA	1 <i>Sv</i>	ICRP 1991 (used) RADS (proposed)
JAXA	0.5 – 1 <i>Sv</i> (3% fatal cancer)	LCM (used)
CSA	1 <i>Sv</i>	ICRP 1991 (used) DALY (proposed)
RSA	1 <i>Sv</i> (7% fatality)	Russian model

- ISS missions (~100-200 *mSv*) are well below current dose limits, so, **disagreement among agencies has not caused mission conflicts.**



IR AND BIOLOGICAL EFFECTS

- **Ionizing Radiation:** Biological effects arise not only from the amount of energy (per unit mass) deposited, but also from the proximity of these energy depositions in critical biological targets (e.g., DNA) in the nm- μ m scale.
- Different particles/energies (**radiation quality**) produce distinct energy patterns that correlate to the biological effectiveness of the radiation.



RELATIVE BIOLOGICAL EFFECTIVENESS

To describe **radiation quality**, the concepts of RBE/ Q are used.

- RBE is the ratio of the doses between a reference radiation (D_{ref}) (e.g., γ -rays) and a radiation under study (D_{test}), that produce the same biological effect.
- RBE is highly influenced by the dose and dose rate, the tissue/organ irradiated, the biological endpoint, and the radiation quality (type/energy of radiation).

Relative Biological Effectiveness (RBE) : $\text{RBE} = \frac{D_{\text{ref}}}{D_{\text{test}}}$

The Quality Factor (Q , w_R) is the average RBE for stochastic effects (e.g., cancer induction).



RESEARCH OBJECTIVE

Our goal is to reduce the uncertainty in astronaut cancer risk assessment:

- I. Use **microdosimetry** to evaluate the quality factor (Q) of space radiation.
- II. Develop a semi-analytic model of lineal energy (y) with input from **Geant4-DNA physics and simulations**.

WHY MICRODOSIMETRY ?

- I. Microdosimetry is fundamentally more suitable for quantifying “dose” at the (sub) cellular level (e.g., DNA scale).
- II. Microdosimetric quantities correlate better with biological response.
- III. Microdosimetric quantities, like lineal energy (y), are directly measurable by on-board instruments (e.g., TEPC).



MICRODOSIMETRY

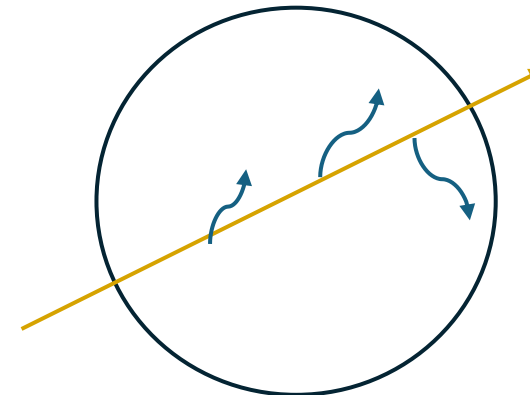
- Microdosimetry deals with the **stochastic aspects** of radiation interactions, which are most pronounced in nanometer/micrometer target volumes.
- *LET* is not suitable at this scale (nm- μm) due to the neglect of energy-loss fluctuations and the finite range of secondary electrons and should be replaced by its stochastic analog called lineal energy (y).
- The value of y depends on the target size (e.g., sphere diameter, d) which must be optimized according to the application (typical values of d range from 10-1000 nm).

Lineal Energy

$$y = \frac{\epsilon}{l}$$

Dose-averaged
lineal energy

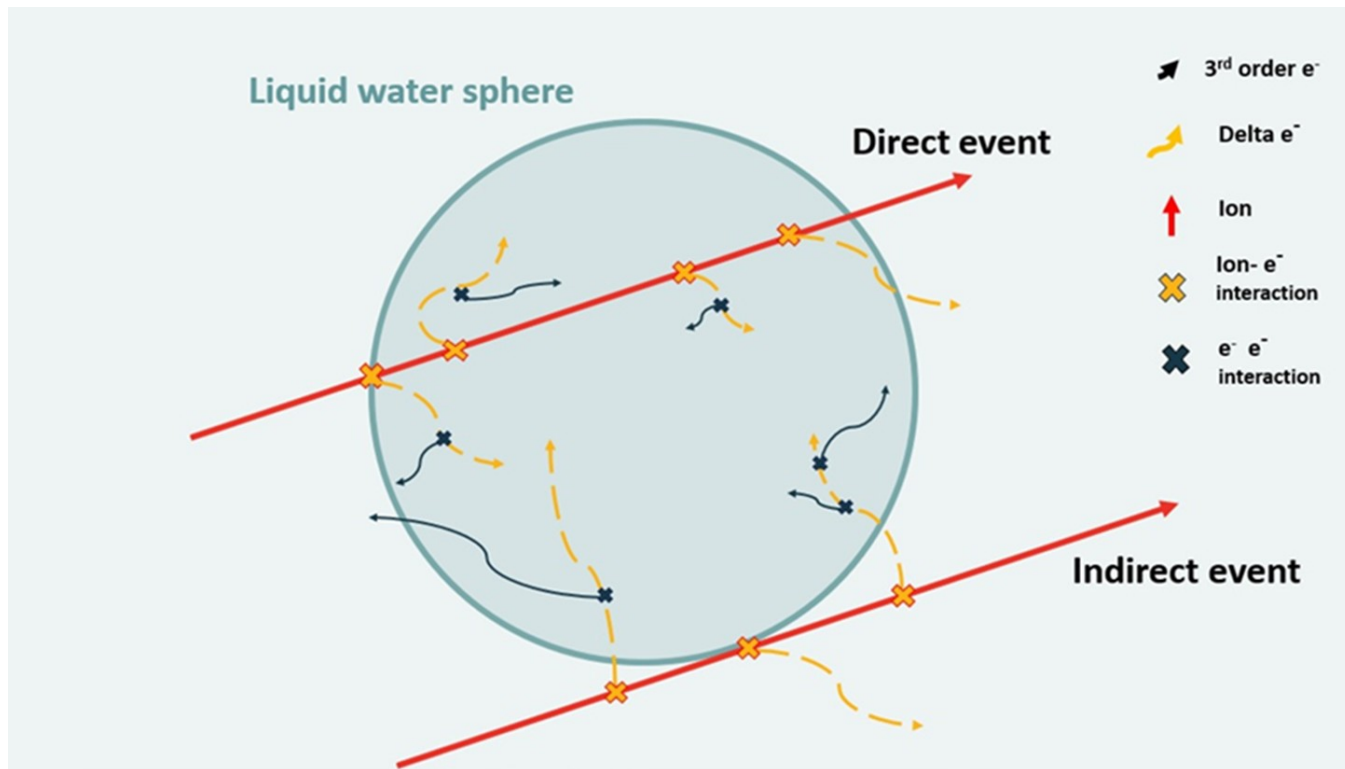
$$y_D = \frac{\int y^2 f(y) dy}{y_F}$$



SEMI ANALYTIC MICRODOSIMETRIC MODEL OF y_D

$$y_D = \underbrace{\left(\frac{LET_{\Delta}}{LET}\right) y_{D,direct}}_{\text{Ion contribution}} + \underbrace{\left(1 - \frac{LET_{\Delta}}{LET}\right) y_{D,indirect}}_{\delta\text{-ray contribution}}$$

$\Delta=0.2\text{-}6\text{ keV}$
Depending on the target size and the penetration depth of the electrons



THE ROLE OF GEANT4-DNA

Geant4-DNA provides the critical physical input for determining both $y_{D,direct}$ and $y_{D,indirect}$:

- i. The δ -ray energy-loss straggling parameter for ions (used in $y_{D,direct}$) is determined by the recently developed (ESA-funded BIORAD III project) **DNA-Opt4X** physics model (Kyriakou et al. *Appl Sci* 2025).
- ii. The values for $y_{D,indirect}$ are determined by interpolation from a pre-calculated set of Geant4-DNA microdosimetric data.
- iii. **IMPORTANT:** The recent extension of **DNA-Opt4X** up to 10 MeV permits simulations over the whole δ -ray spectrum for most SPE and GCR ions.



PRESENT DEVELOPMENTS ON A MICRODOSIMETRIC QUALITY FACTOR (QF)

- 1. First step (ESA-funded BIORAD III program):** The QF was evaluated by the Theory of Dual Radiation Action (TDRA) at the low-dose limit:

$$Q_{TDRA D \rightarrow 0} = \frac{y_{D,test}^*}{y_{D,ref}^*}$$

the $y_{D,ref}^*$ of ^{60}Co is used for reference

$y_{D,test}^*$ is calculated for a sphere with diameters of 10 nm – 1

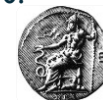
$$\text{where } y_D^* = \frac{1}{y_F} \int_0^\infty y_o^2 \left[1 - \exp\left(-\frac{y^2}{y_o^2}\right) \right] f(y) dy$$

is the saturated dose-weighted lineal energy with $y_o = 125 \text{ keV}/\mu\text{m}$ being the peak value of lineal energy before the overkill.

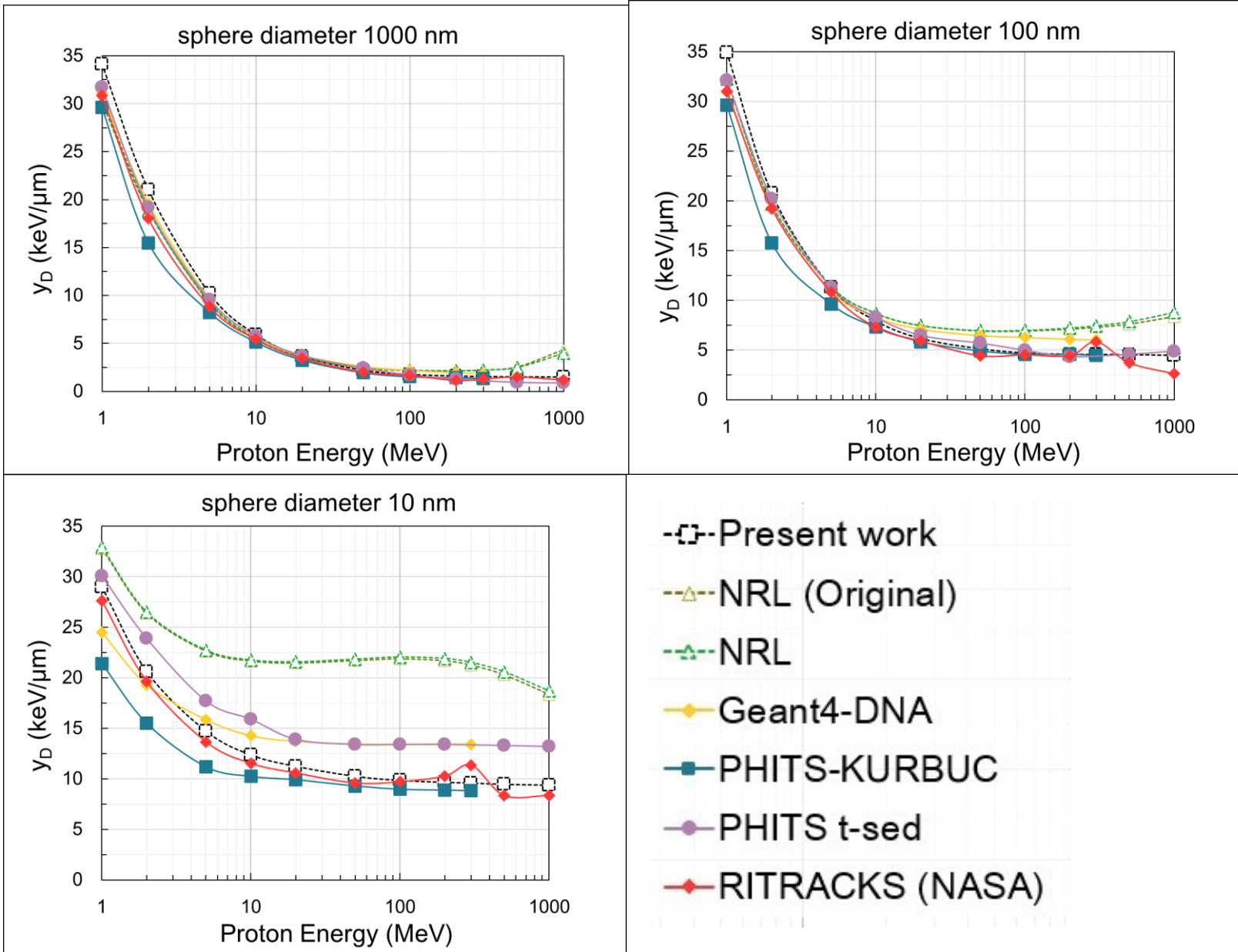
- 2. Second step (in progress):** The full-TDRA model (i.e., for any dose level) will be combined with the Linear Quadratic (LQ) model to yield semi-empirical α, β parameters as a function of y_D^* .



The research was selected via the Open Space Innovation Platform (<https://ideas.esa.int>) as a Co-Sponsored Research Agreement and carried out under the Discovery program of, and funded by, the European Space Agency. Grant number 4000147290.



y_D : ANALYTIC MODELS VS. MONTE CARLO TRACK STRUCTURE (MCTS) DATA



The present model is much closer to MCTS data (<10%) than the NRL analytic models over the whole proton spectrum (1 MeV-1 GeV) and for all sphere diameters.

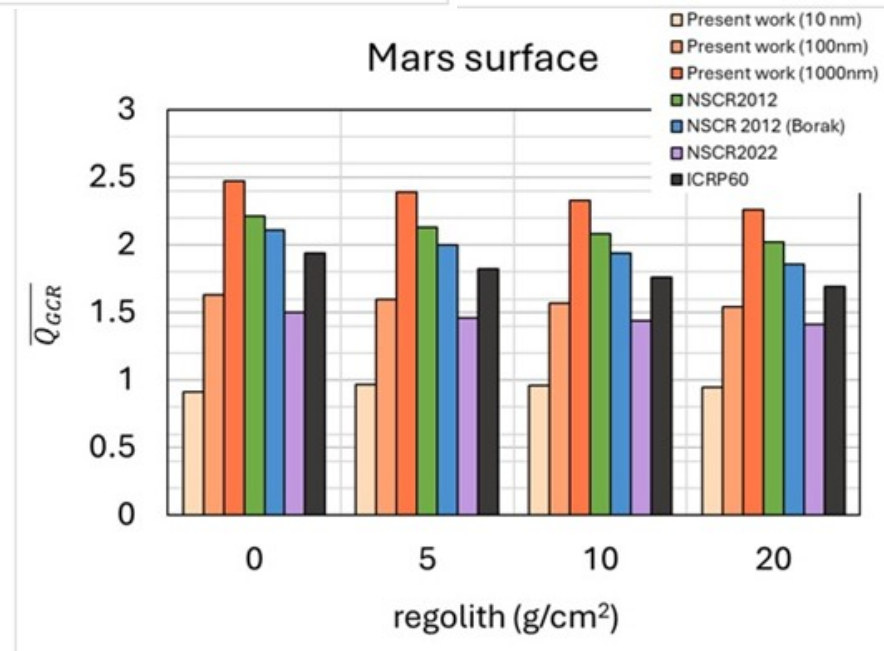
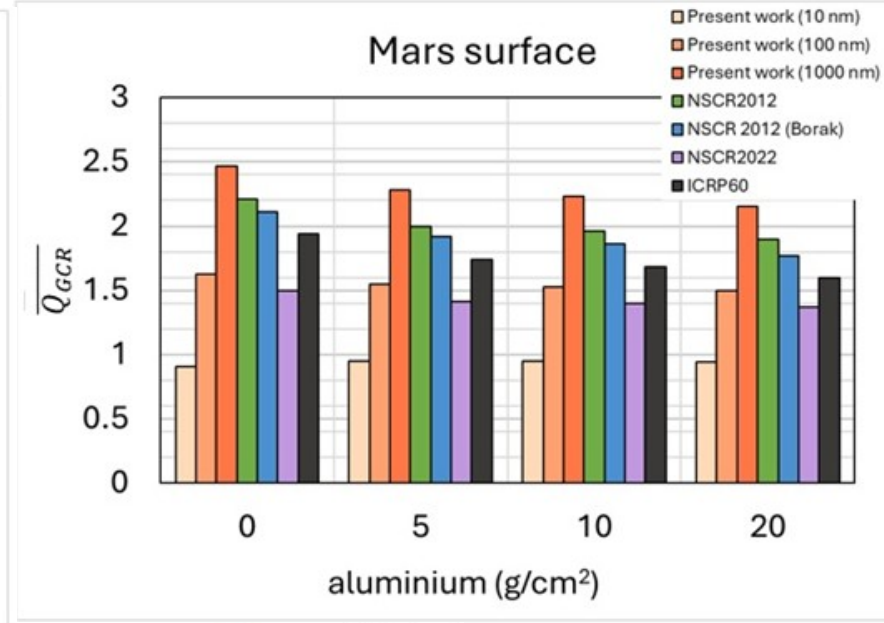
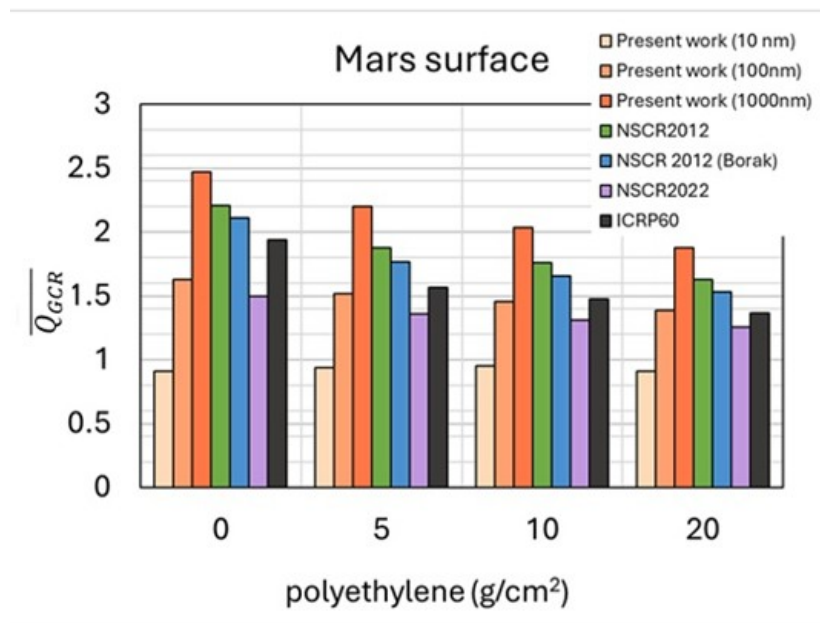


Space mission scenario

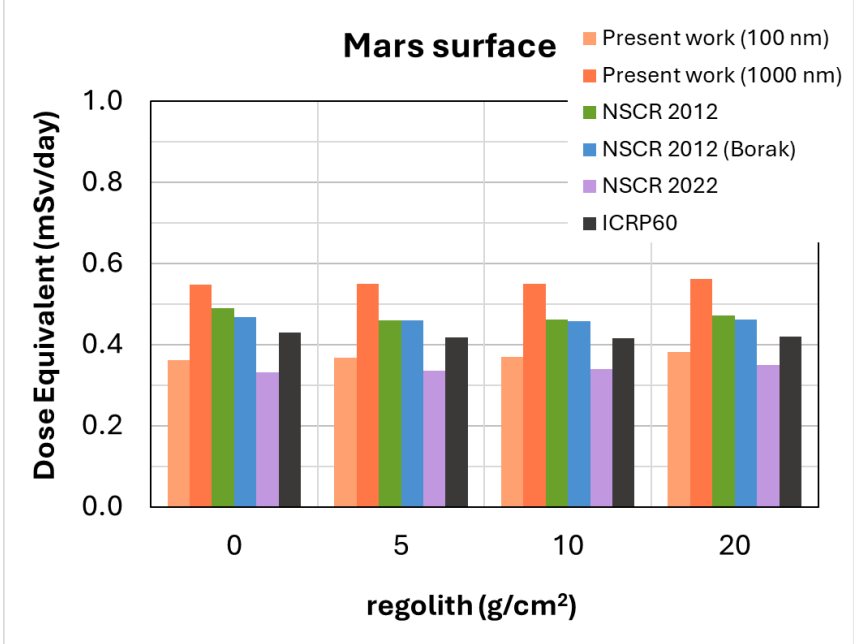
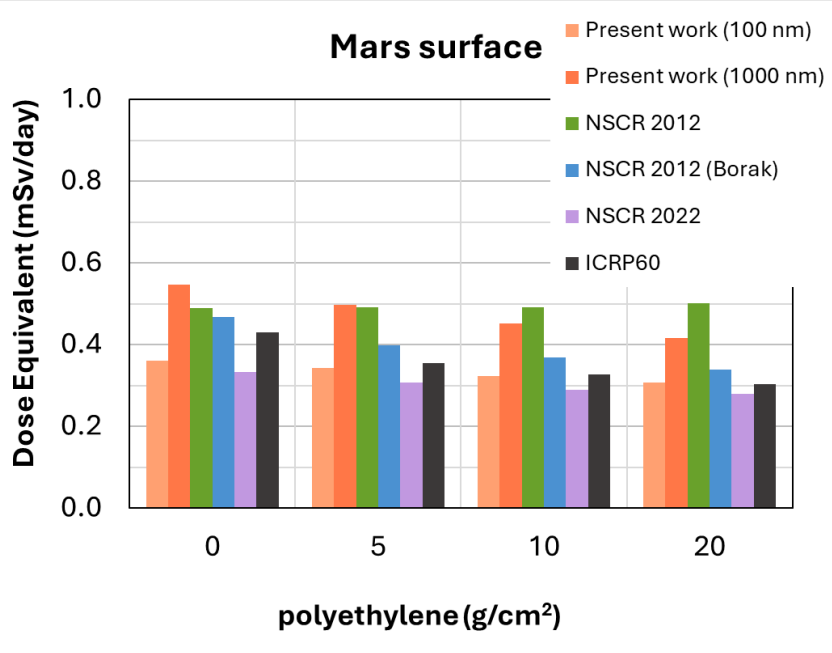
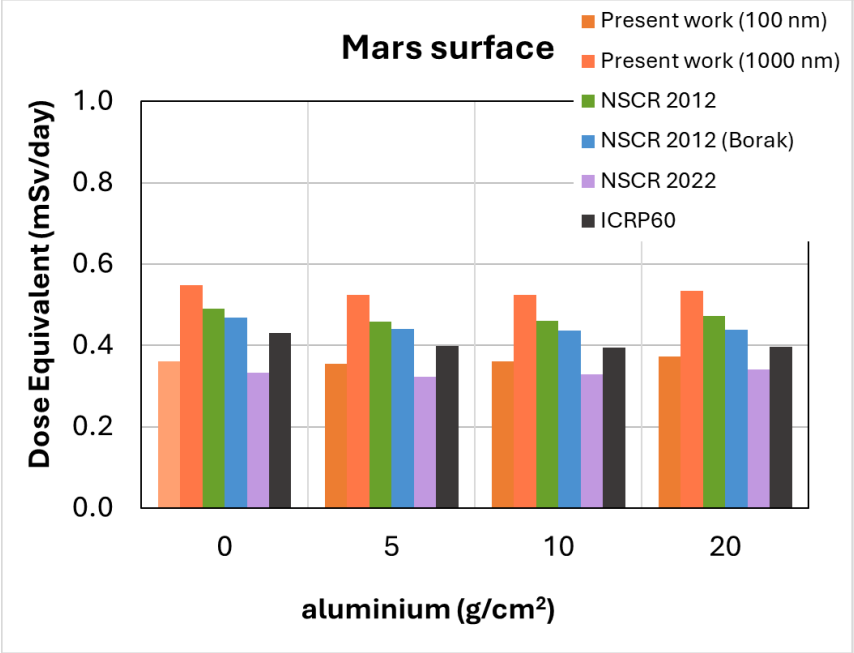
Free space and Martian surface



\bar{Q}_{GCR} FOR MARTIAN SURFACE

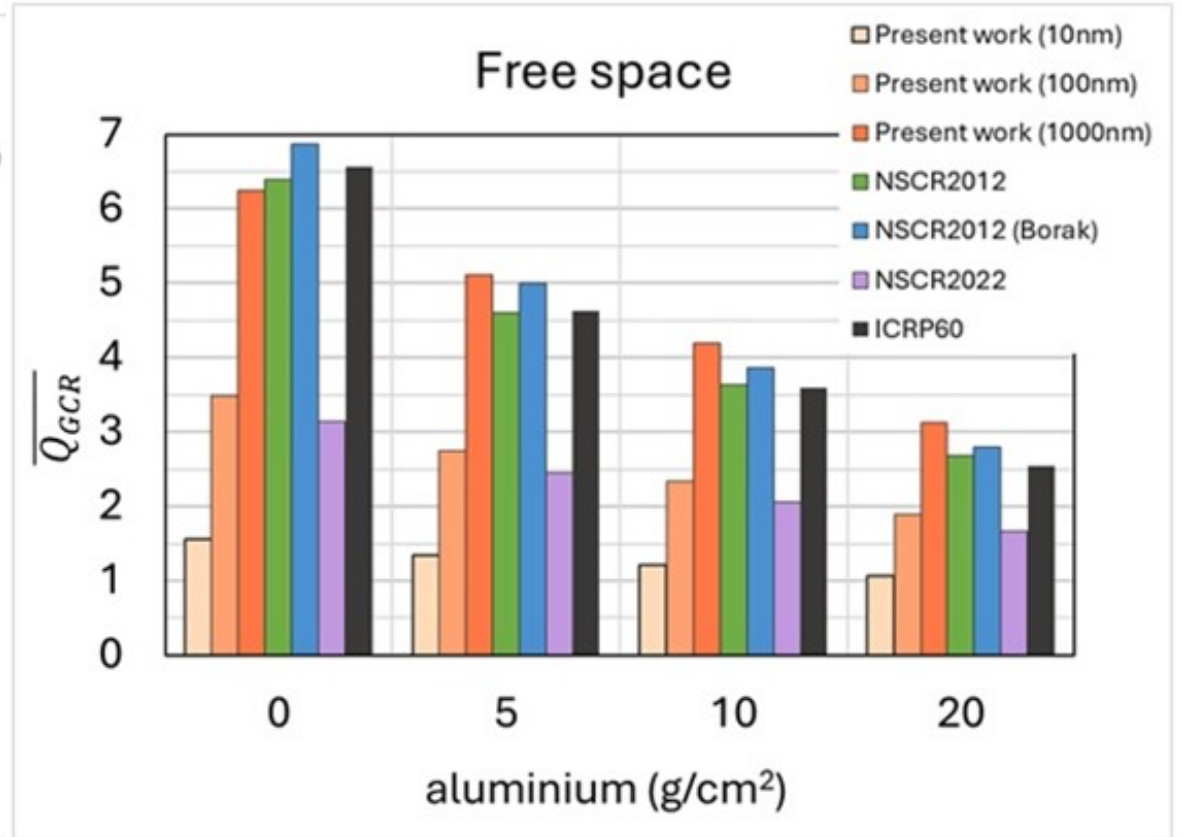
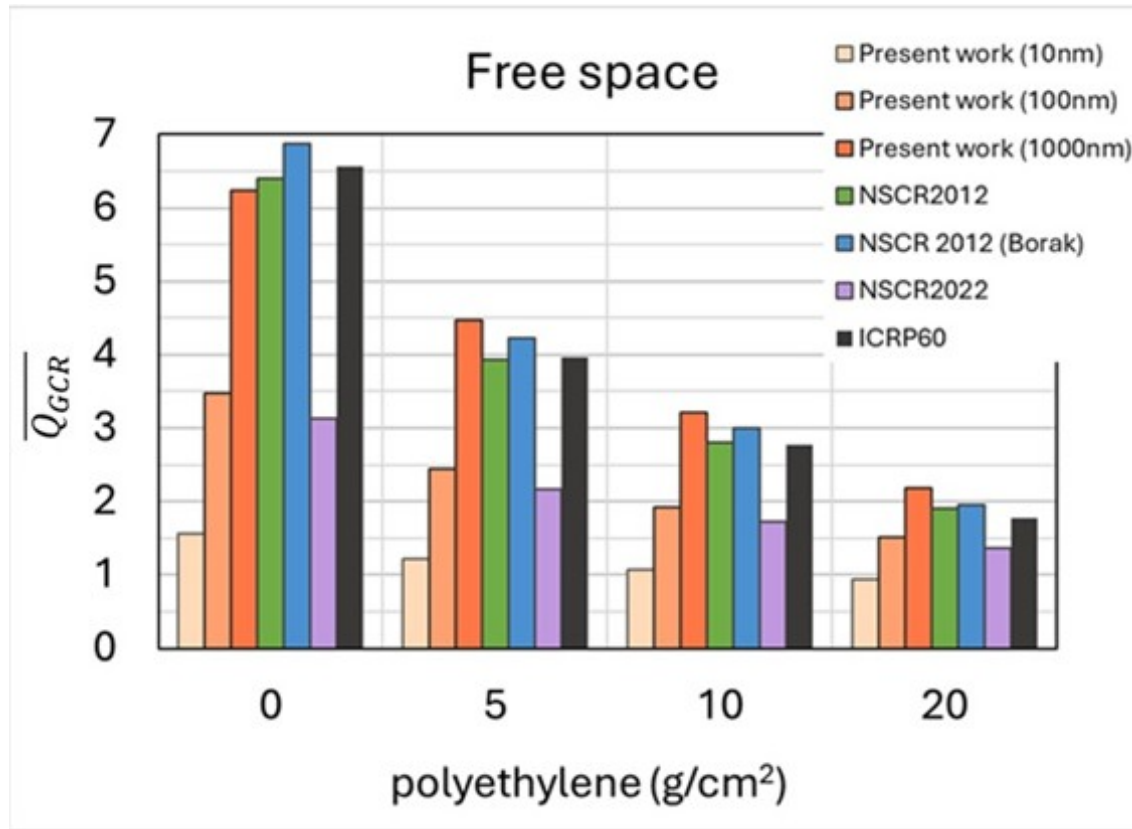


DOSE EQUIVALENT (DE) FOR MARTIAN SURFACE

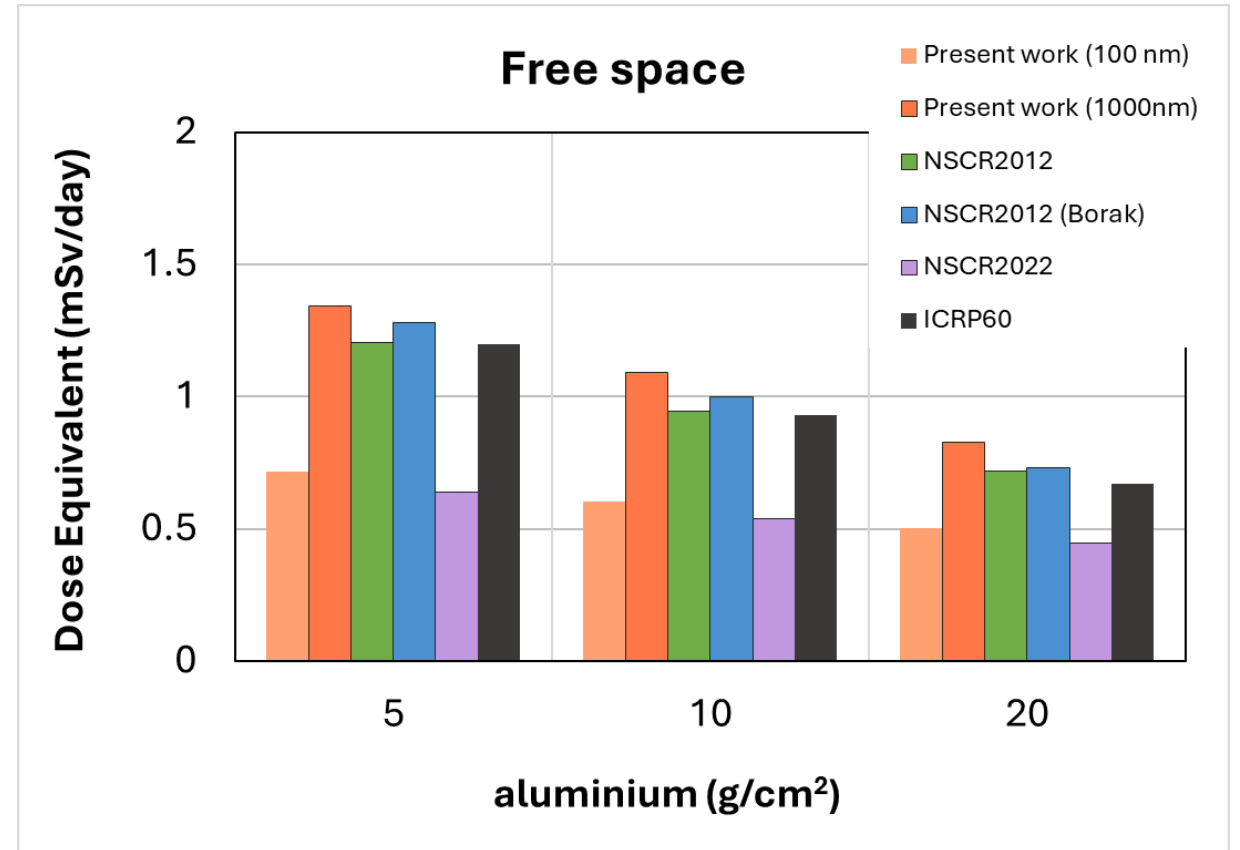
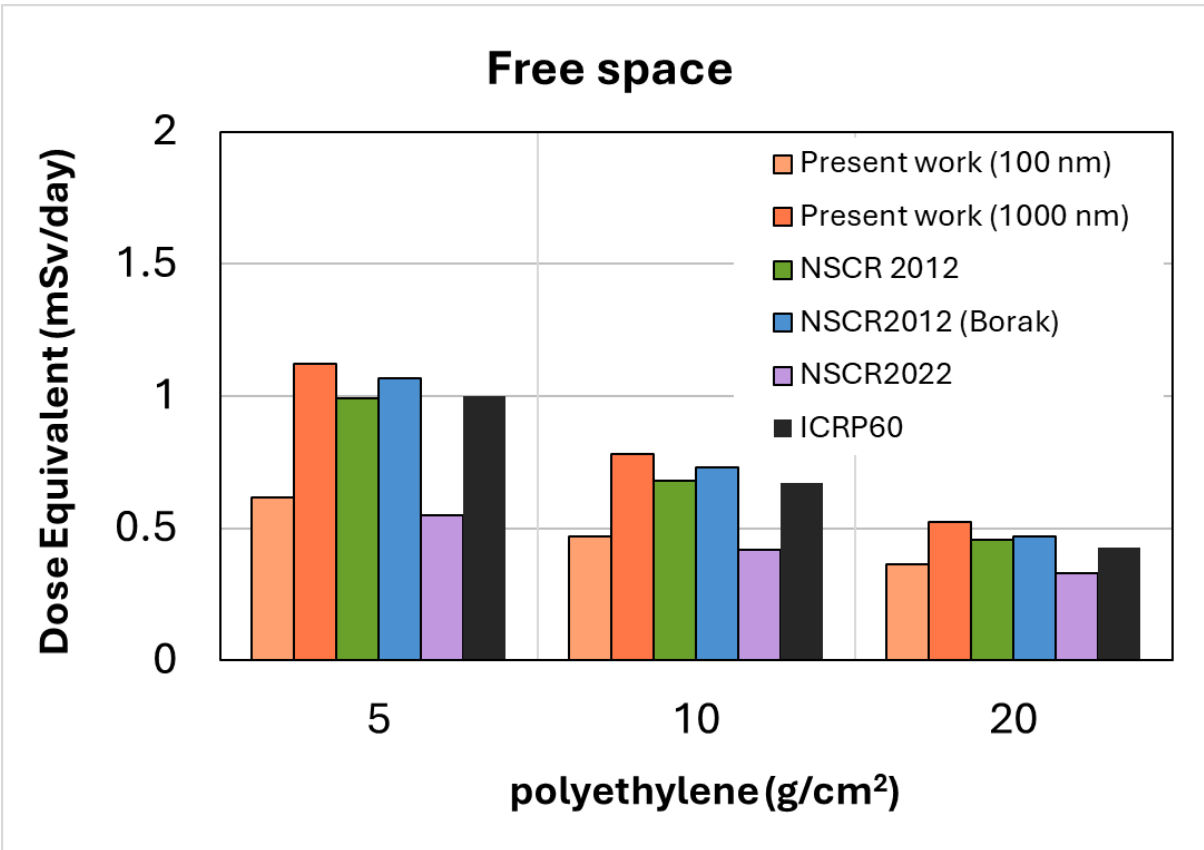


MARTIAN SURFACE:
~0.3 – 0.5 mSv / day
for all methods, different shielding





DOSE EQUIVALENT (DE) FOR FREE SPACE



FREE SPACE:
~0.5 – 1.5 mSv /day
for all methods, different shielding



DISCUSSION

- Impact of model (TDRA, NASA, ICRP): Up to a factor of 2.5 variations of Q were observed among the different Q models, consistent across all shielding configurations (aluminium, regolith, polyethylene) and radiation environments (free space and the Martian surface).
- Impact of target size: Our Q model at 1000 nm agrees better with earlier NASA's Q model (2012) and ICRP Publication 60 whereas our Q model at 100 nm agrees better with NASA's most recent Q model (2022). Our Q model at 10 nm exhibited the worse agreement with both NASA's models and ICRP 60.
- Martian surface vs. deep space: \bar{Q}_{GCR} is consistently lower on the Martian surface (≤ 2.5) than the free space (≤ 6), independent of model and for the same shielding material.
- Impact of shielding: Polyethylene presents lower Q values than aluminium/regolith.
- Free space: both Q and DE decrease with increasing shielding thickness ($5 - 20 \text{ g/cm}^2$).
- Martian surface: both Q and DE remain unaffected by shielding thickness ($5 - 20 \text{ g/cm}^2$).
- Our predictions confirm that the DE on Martian surface is by a factor of 2-3 lower than in deep space but still 30-60 times higher than on Earth.



The adopted Q values have a direct impact to mission planning:

The meaning of “safe days”: the maximum days an astronaut can stay in space without exceeding the dose limits.

$$\textit{Safe Days} = \frac{\textit{Dose limit}}{\textit{Dose equivalent per day}} = \frac{\textit{Dose limit}}{\textit{Dose} \times Q} = \frac{\textit{const}^2}{\textit{const}^1} \times \frac{1}{Q} \sim Q^{-1}$$

The safe days are inversely proportional to Q , i.e., a factor of 2 variation across different Q models may reduce or increase the mission days by the same factor.

¹constant for a specific radiation environment and transport code

²constant for a specific space agency



FUTURE WORK

- Combine the full-TDRA model (applicable to any dose level) with the LQ model to deduce α , β parameters as a function of y_D^* .
- Extend the δ -ray contribution to y_D^* to ion energies up to 100 GeV.
- Develop proton ionization cross sections based on **DNA-Opt4X** to offer a coherent approach for protons and delta-ray electrons.
- To further speed up the computations, develop analytic parametrizations of y_D^* as a function of electron/ion energy and ion atomic number.
- Create an example application to Geant4-DNA for astronaut risk assessment.





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Thank you!

