Comparative study on space radiation dosimetry in the International Space Station and Artemis-I Orion with two different quality factors

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Outline

- Space radiation environment & dose measurement by passive detectors
- Quality factors; Q_{ICRP}, Q_{NASA}, and Q*
- MARE experiment on Artemis-I & measurement results
- Summary

Space radiation environment

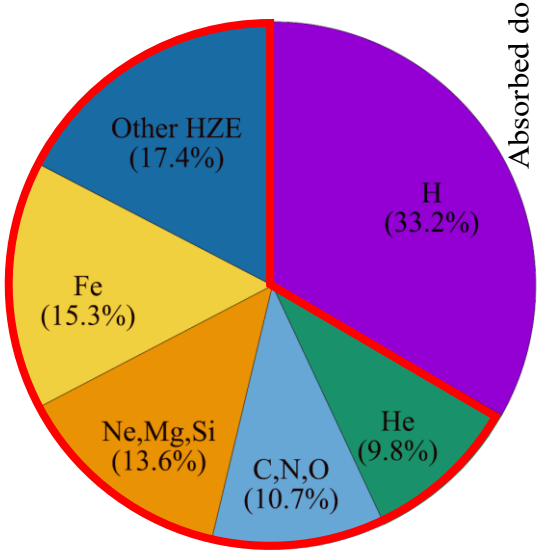
- Space radiation consists of high energy charged particles originating from solar energetic particles and galactic cosmic rays.
- Dose exposure levels in space corresponds to
  - ➢ ~200-300 mSv/yr on the ISS orbit
    (No atmosphere, Kodaira et al., RM 2013)
  - ➢ ~600-700 mSv/yr in the deep space
    (No atmosphere & no geomagnetic fields, Zeitlin et al., Science 2013)

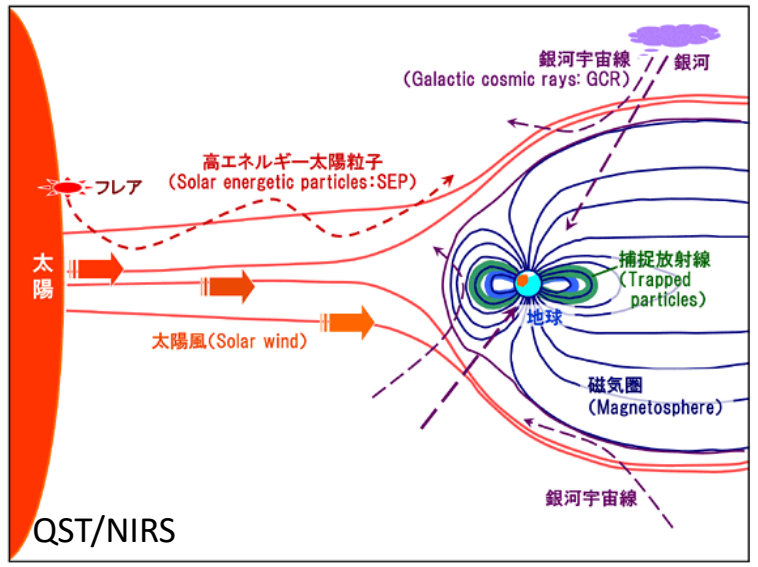
For future prolonged space stays,

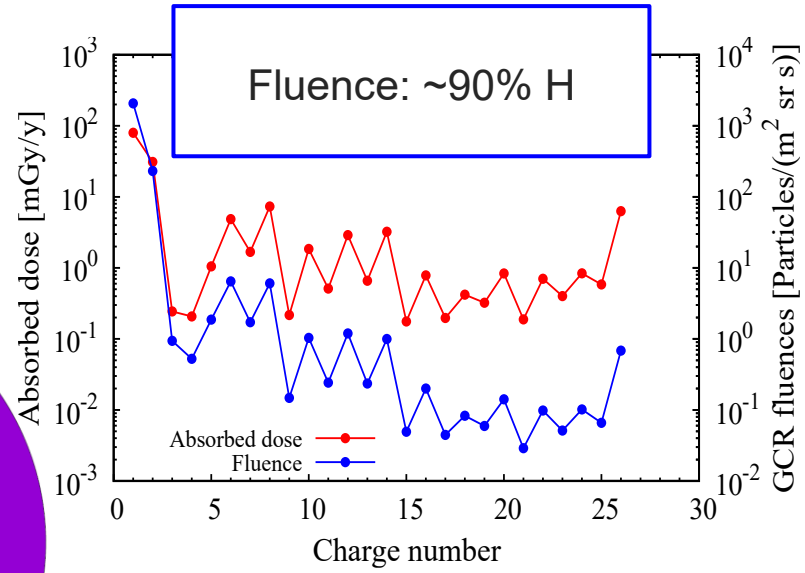
✓ **Dose assessment**

✓ Radiation shielding

are crucial from the aspect of radiation.







Dose equivalent:
>60% HZE

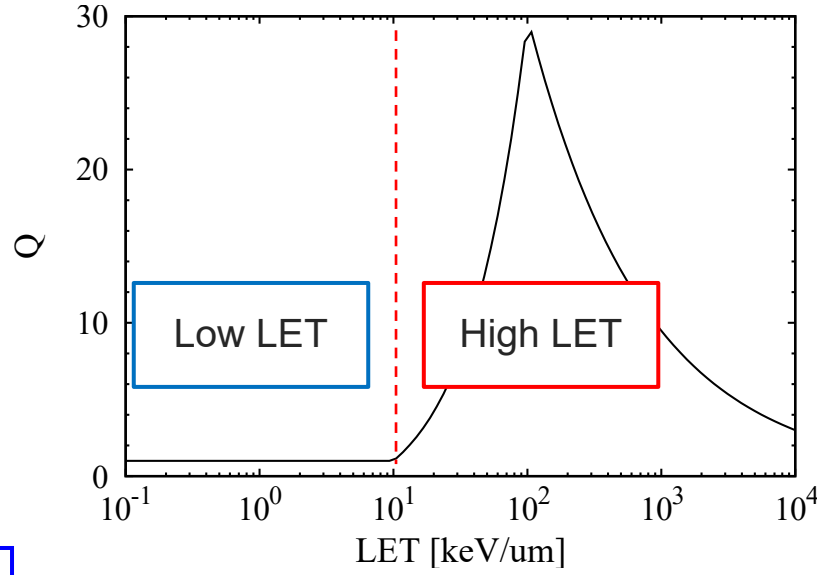
Dose assessment using OSLD and CR-39

Dose exposure was measured combining two detectors.

【Low LET (<10 keV/μm)】

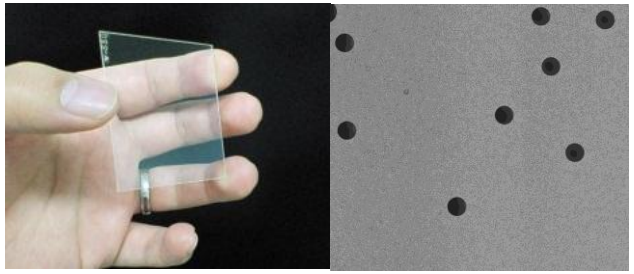
Optical Stimulated Luminescence Detector (OSLD)

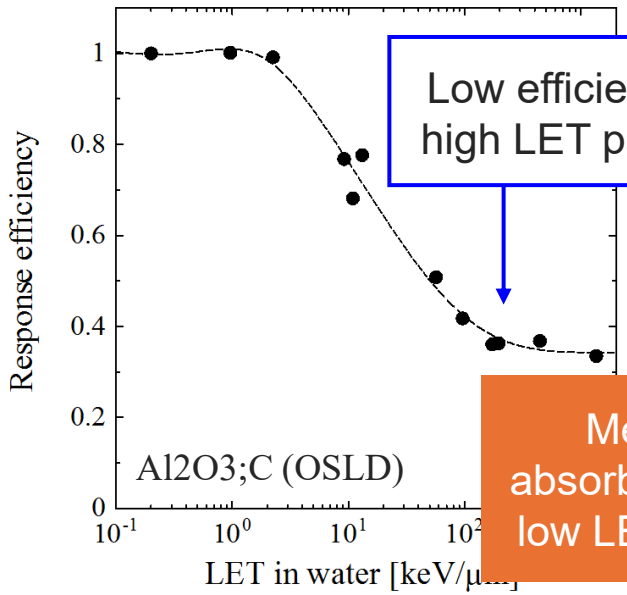




【High LET (>10 keV/μm)】

CR-39 plastic nuclear track detector





Low efficiency for high LET particles

Quality factor

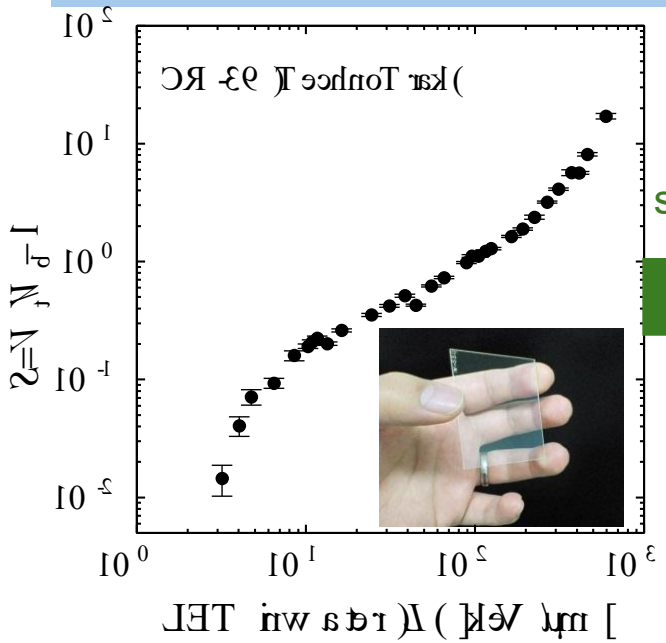
Low LET threshold: ~3.5 keV/μm

Measures absorbed dose by low LET particles

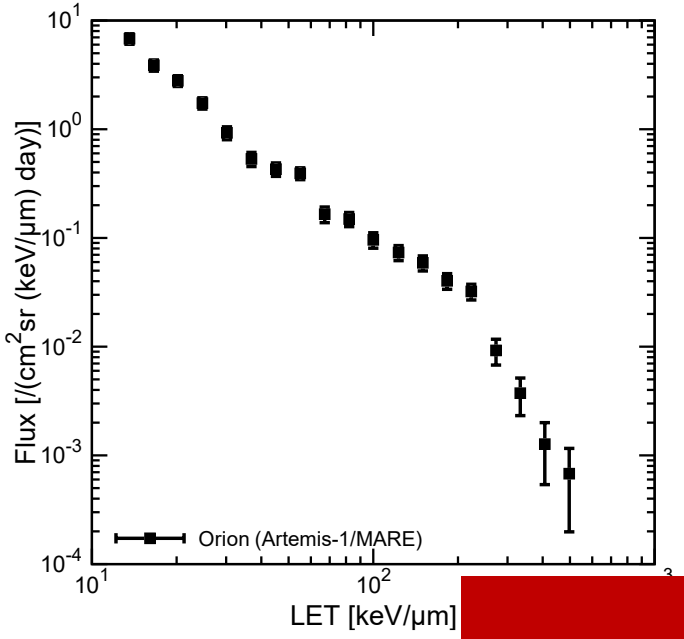
Total absorbed dose and dose equivalent

Measures LET spectrum by high LET particles

Dose assessment using OSLD and CR-39



LET spectrum

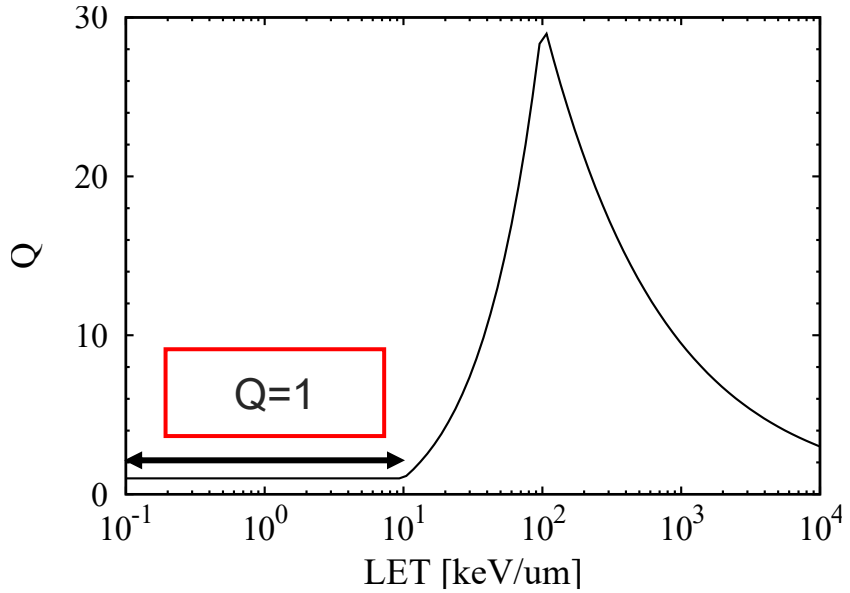


Dose exposure by high LET particles

$$D = \frac{k}{\rho}\sum_i F_i \cdot LET_i$$

$$H = \sum_i Q_i \cdot D_i = \frac{k}{\rho}\sum_i Q_i \cdot F_i \cdot LET_i$$

k: Conversion constant from eV to J



Total dose exposure

Absorbed dose *D*:

$$D = D_{\leq 10keV/\mu m} + D_{>10keV/\mu m}$$
$$= (D_{LD} - \kappa D_{CR-39}) + D_{CR-39}$$
$$= D_{LD} + (1-\kappa)D_{CR-39}$$

Dose equivalent *H*:

$$H = D_{\leq 10keV/\mu m} + H_{>10keV/\mu m}$$
$$= (D_{LD} - \kappa D_{CR-39}) + H_{CR-39}$$

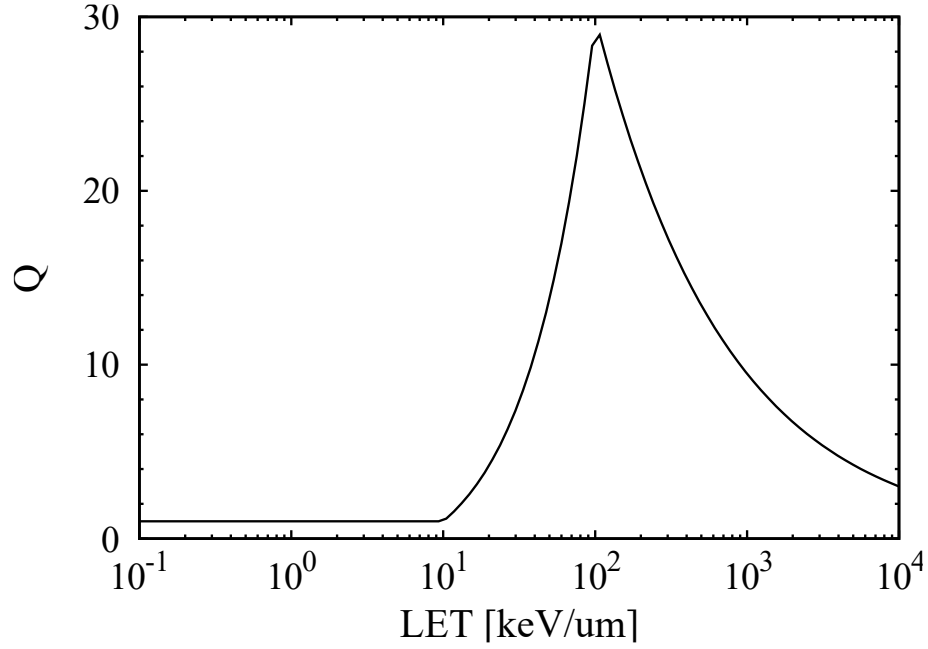
κ: proportional constant (Doke et al., RM 1995)

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Quality factors

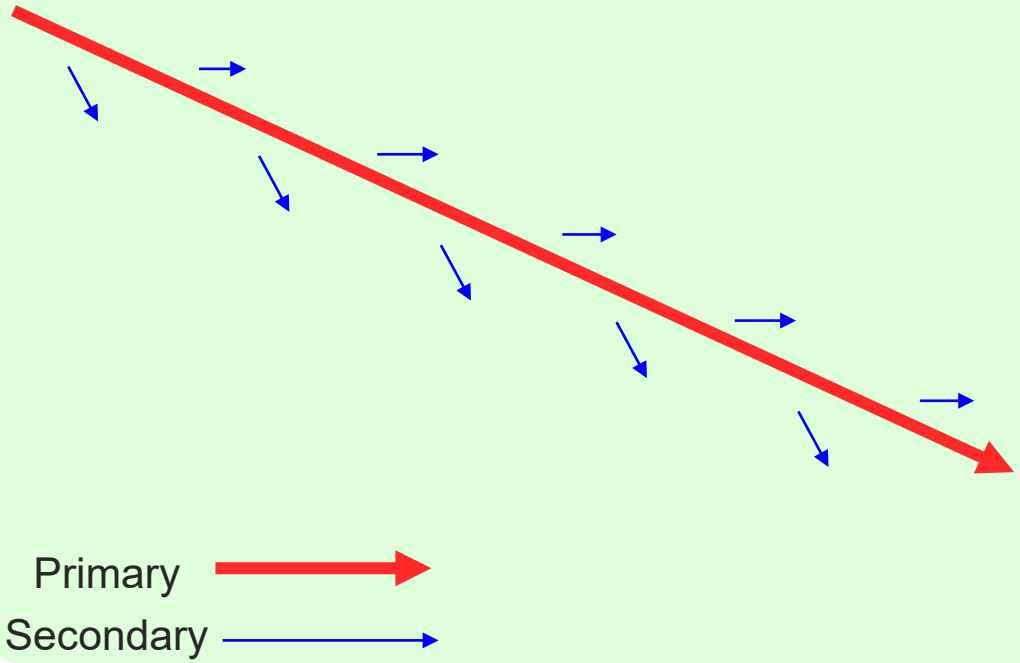
Q_{ICRP} (ICRP Pub. 60, 1990)



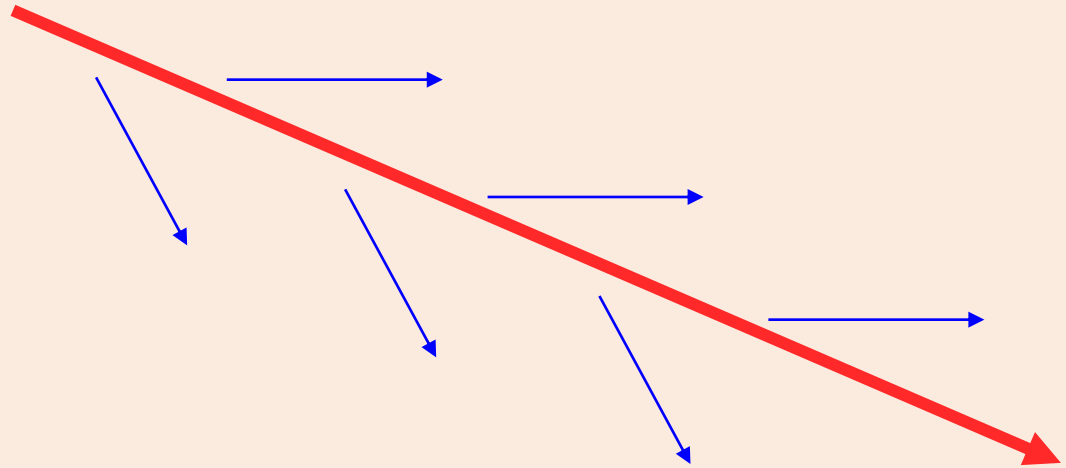
- Simple LET function
- Easy application to LET measurement
- Common values for particles with a specific LET and different charges

Track structure difference for specific LET particles

Small charge⇔Low energy



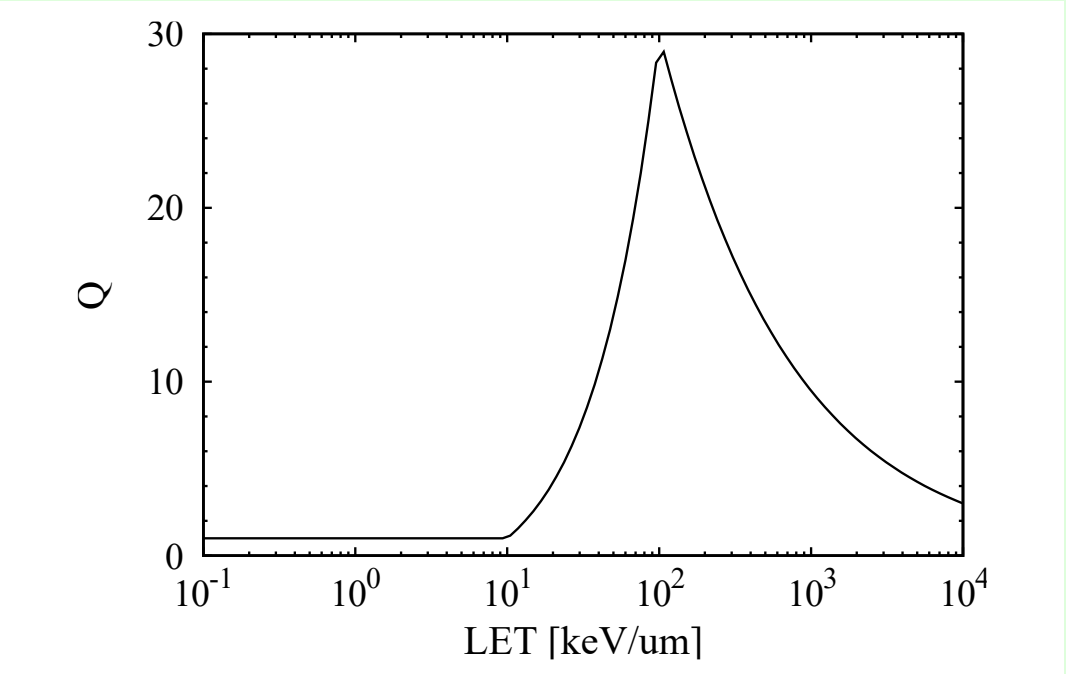
Large charge⇔High energy



The stack structure model considers energy deposit in track core and penumbra.

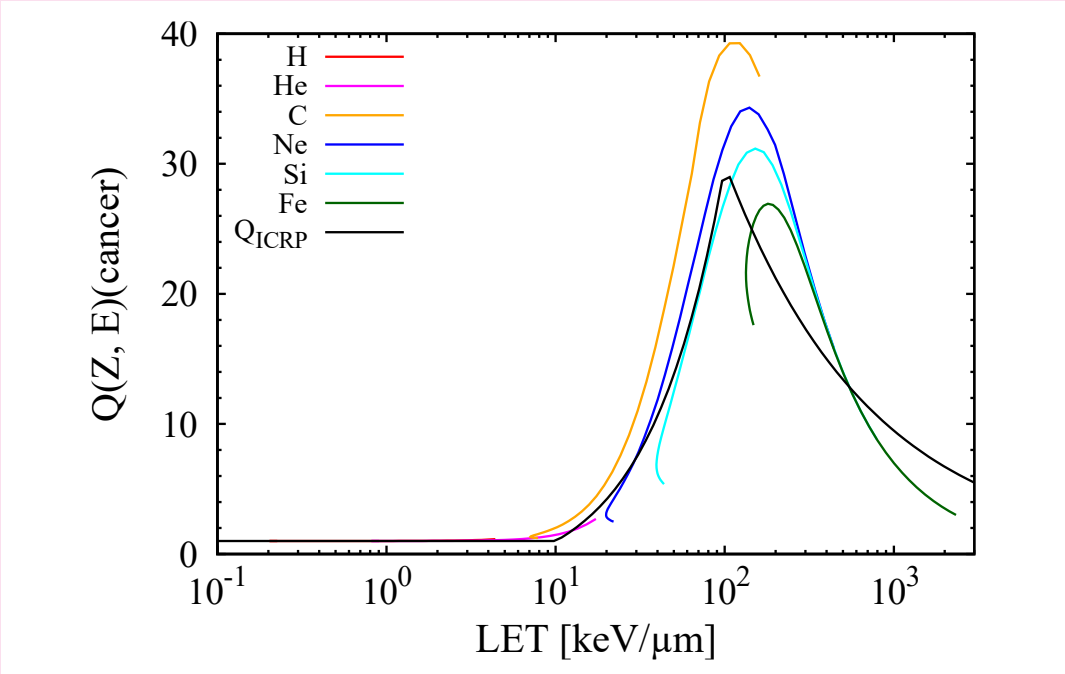
Quality factors

Q_{ICRP} (ICRP Pub. 60, 1990)



- Simple LET function
- Easy application to LET measurement
- Common values for particles with a specific LET and different charges

Q_{NASA} (Cucinotta et al., NASA/TP 2013)



- LET and charge dependent
- Difficult application to LET measurement
- Different values for particles with a specific LET and different charges

Q* approach

We suggested a new quality factor, *Q, which is applicable to LET spectra without fundamental changes in the measurement procedures.**

$$H = \sum_{LET} D(LET) \cdot Q(LET)$$

$$D(LET) = \frac{k}{\rho} F(LET) \times LET$$

$$H = \sum_{LET} \sum_{Z} D(Z, LET) \cdot Q_{NASA}(Z, LET)$$

$$= \sum_{LET} D(LET) \sum_{Z} \frac{D(Z, LET)}{D(LET)} \cdot Q_{NASA}(Z, LET)$$

$$= \sum_{LET} D(LET) \sum_{Z} C(Z, LET) \cdot Q_{NASA}(Z, LET)$$

$$= \sum_{LET} D(LET) \cdot Q^*(LET)$$

Charge contribution rates to absorbed dose at the specific LET:

$$C(Z, LET) = \frac{D(Z, LET)}{D(LET)}$$

$C(Z, LET)$ values **do not vary significantly** with the solar modulation and surrounding shielding thickness.

→ Representative Q* values can be surrogates for Q_{NASA}.

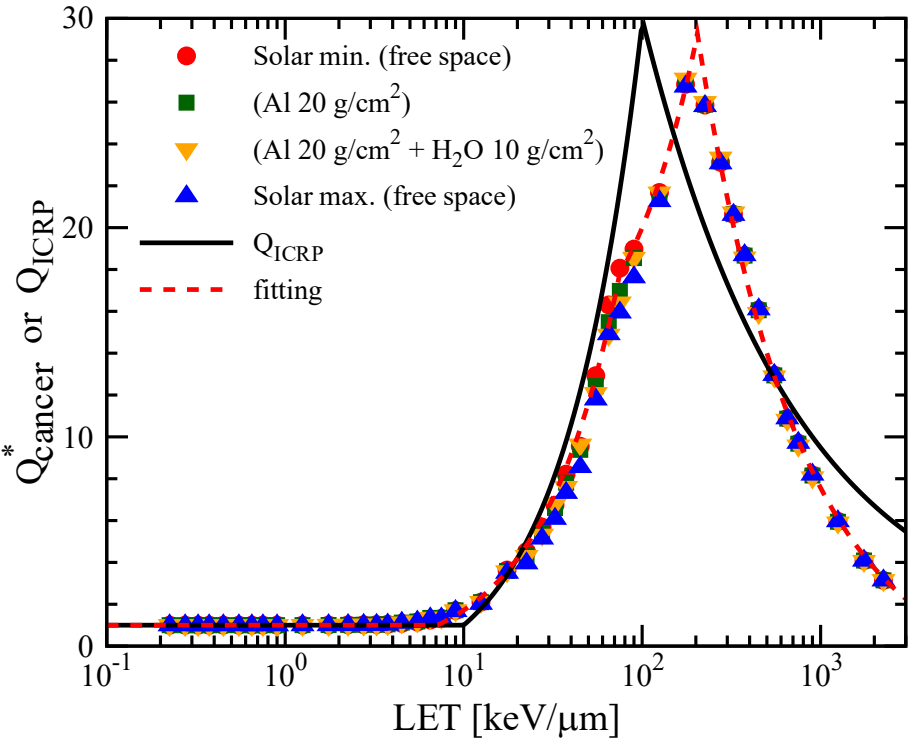
(Naito et al., LSSR 2026)

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$$D(LET) = \frac{k}{\rho} F(LET) \times LET$$



(Naito et al., LSSR 2026)

$T)$

$s_A(Z, LET)$

$s_A(Z, LET)$

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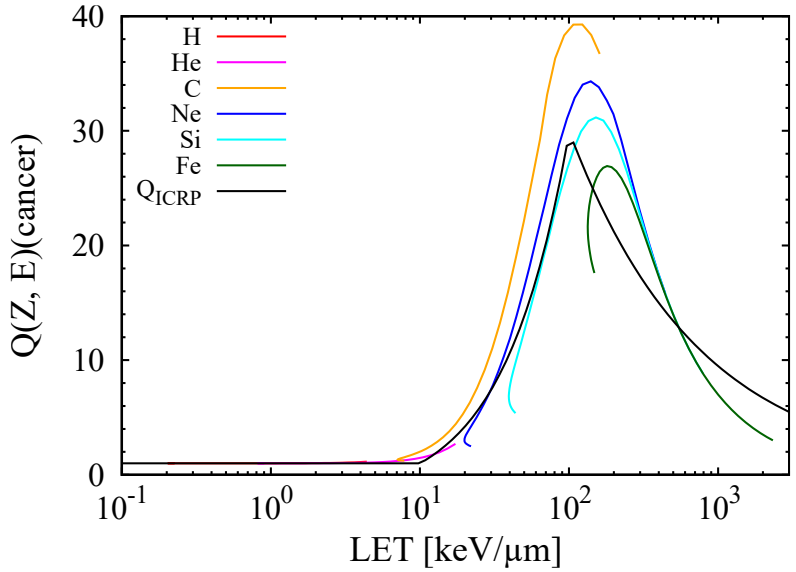
$$C(Z, LET) = \frac{D(Z, LET)}{D(LET)}$$

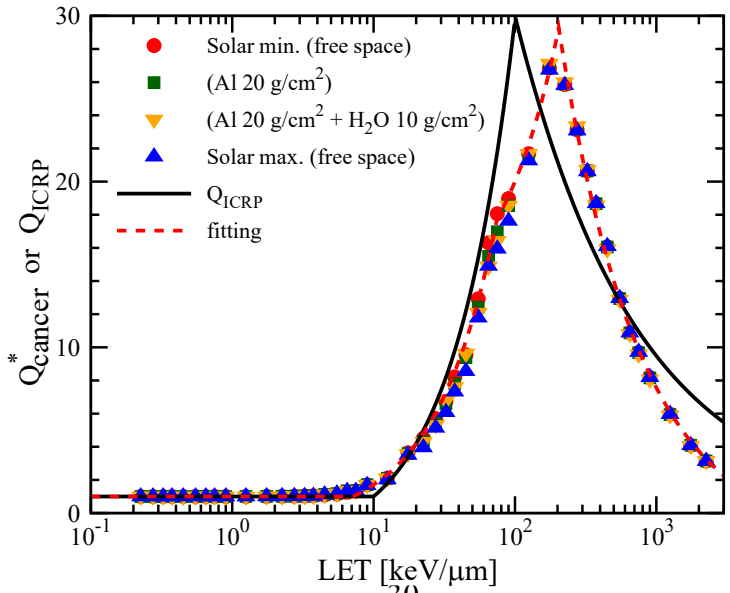
$C(Z, LET)$ values **do not vary significantly** with the solar modulation and surrounding shielding thickness.

→ Representative Q* values can be surrogates for Q_{NASA}.

Q* advantages

✓ **Q^* is directly applicable to the space LET measurements.**





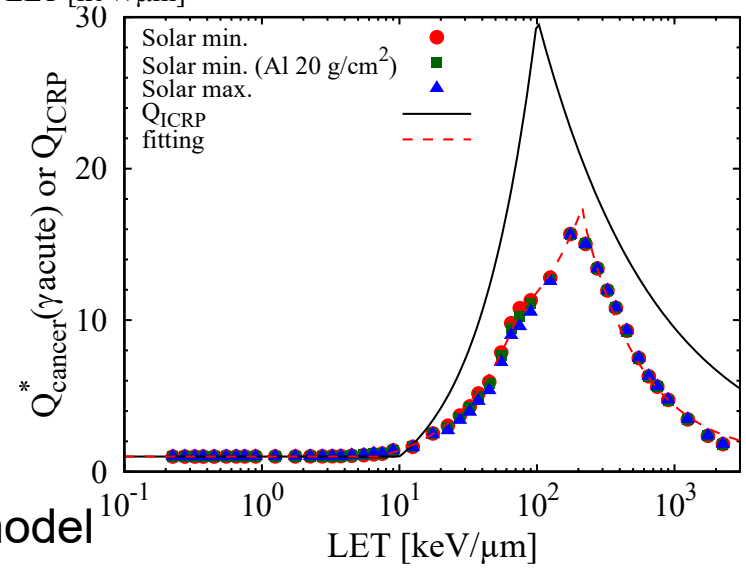
✓ **$C(Z, LET)$ values are independent to the quality factors.**

This approach is also applicable for the other RBE models.

e.g.) $RBE_{\gamma acute}$ model, NTE model, etc...

(Cucinotta, LSSR 2015, Edwards, JRP 1999)

$$RBE_{\gamma acute} = DDREF \cdot \frac{6.24\sigma_0/\alpha_\gamma}{LET} P(Z,E) + 1 - P(Z,E)$$



RBE_{gacute} model

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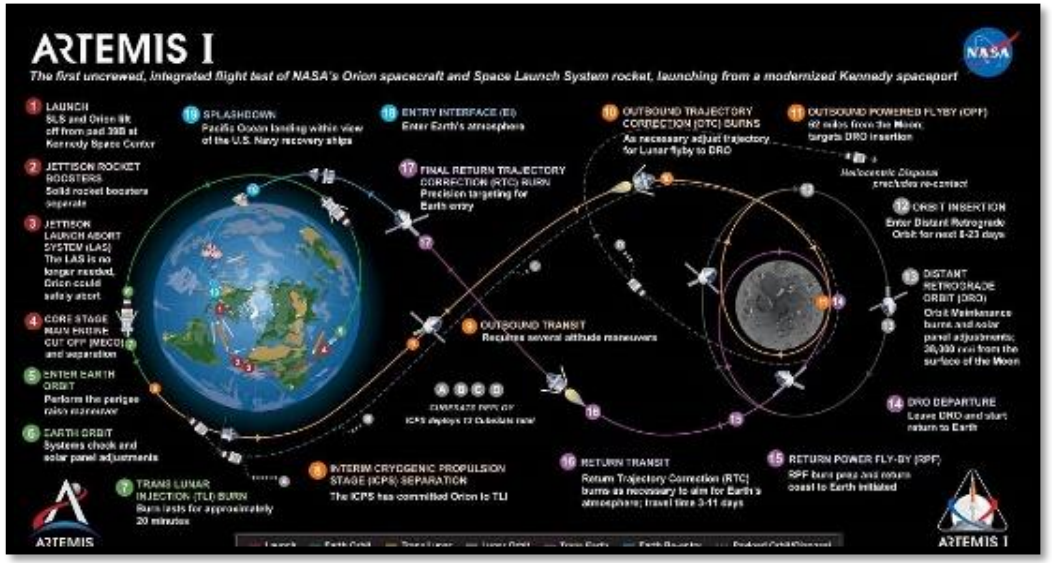
MARE experiment on Artemis-I Orion

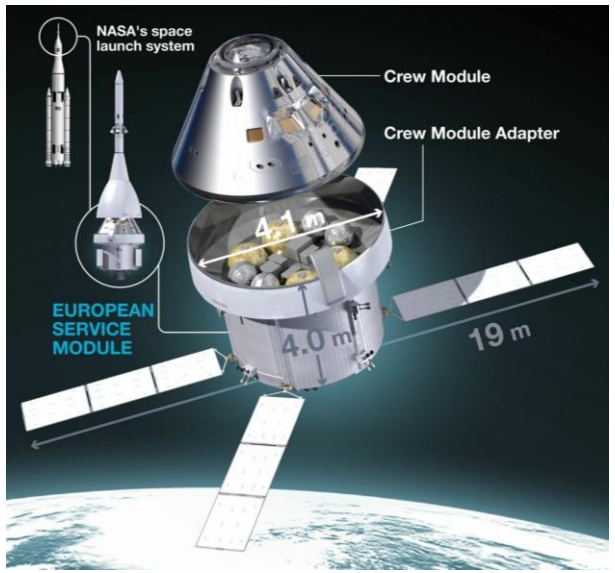
MARE experiment

(Matroshka AstroRad Radiation Experiment)

- International collaboration led by DLR.
- Space radiation dose was measured during the round trip between Earth and Moon.
- Phantoms equip dosimeter packages to obtain dose distribution and to evaluate the shielding effectiveness.

25 days cruise between Earth and Moon
(2022/11/26-2022/12/11)





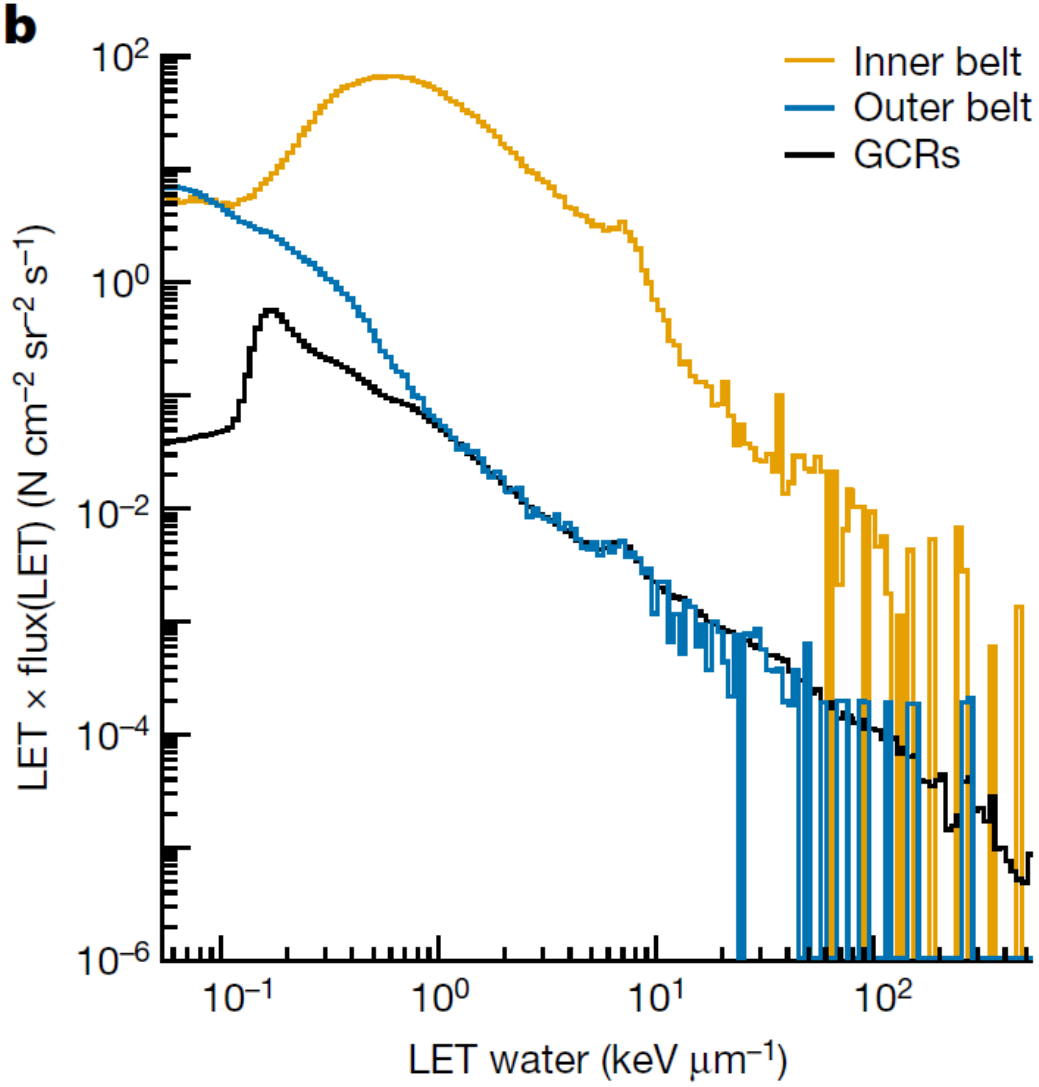






Eight dosimeter packages from QST were installed.
OSLD+CR-39

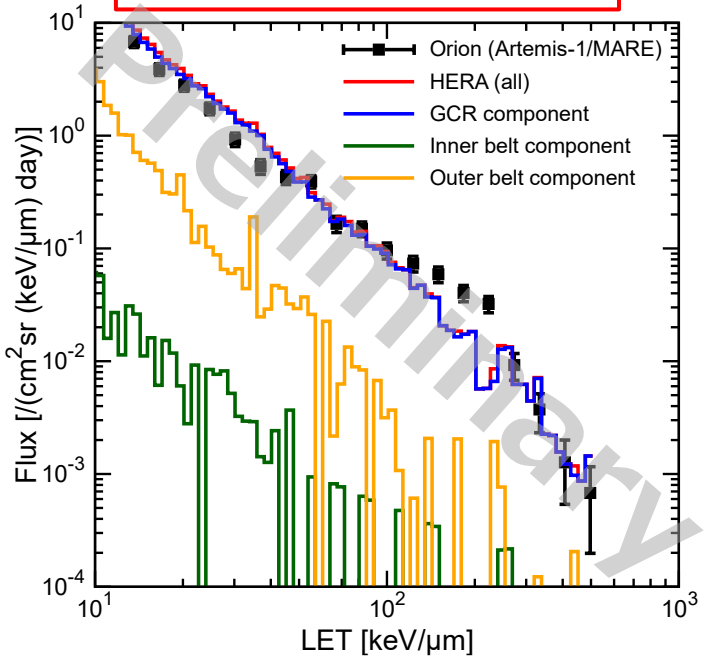
Radiation belt contribution



LET spectra from the HERA HSU2 instrument (George et al., Science 2024)

Correction of the period length

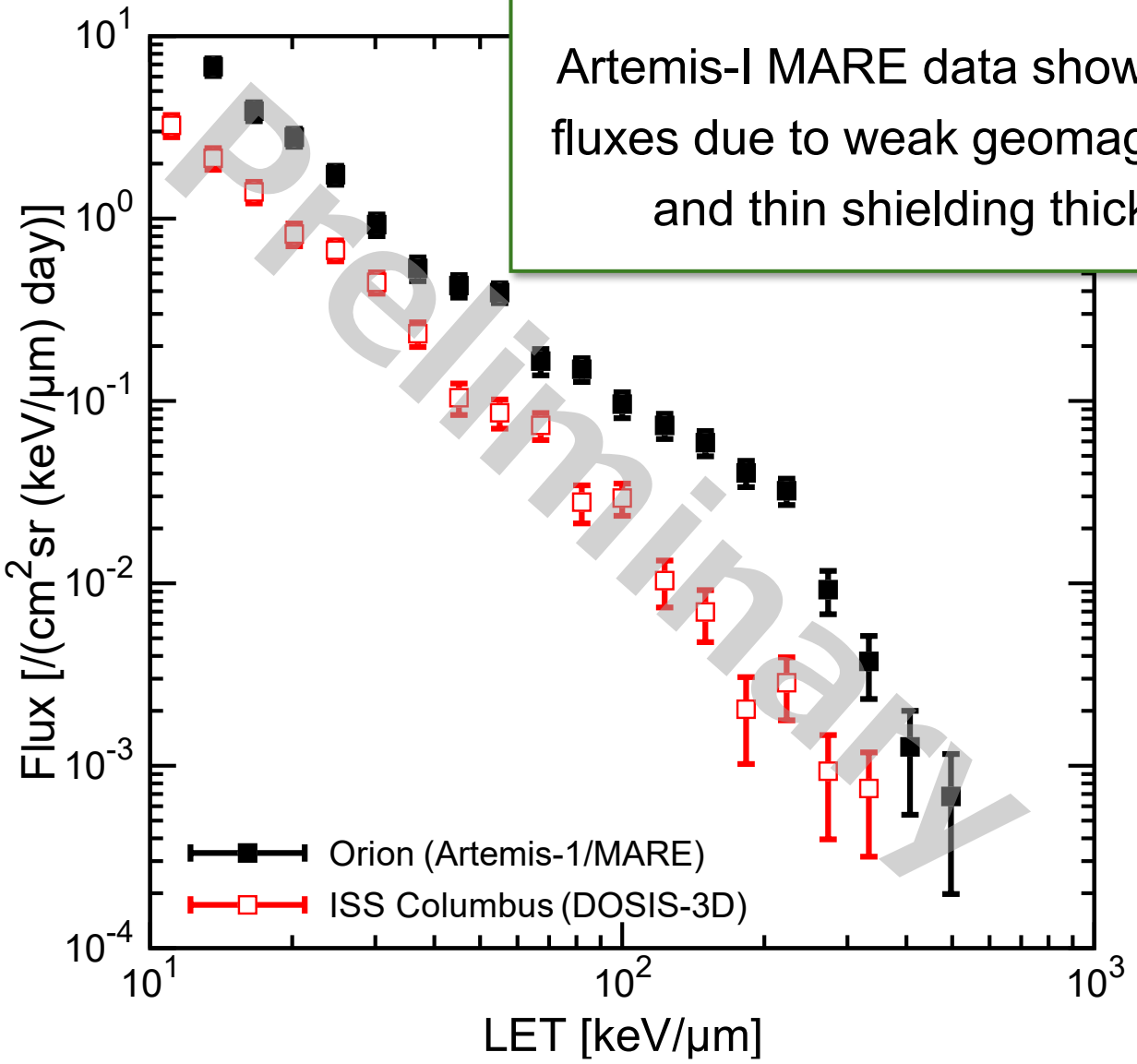
Comparison with CR-39



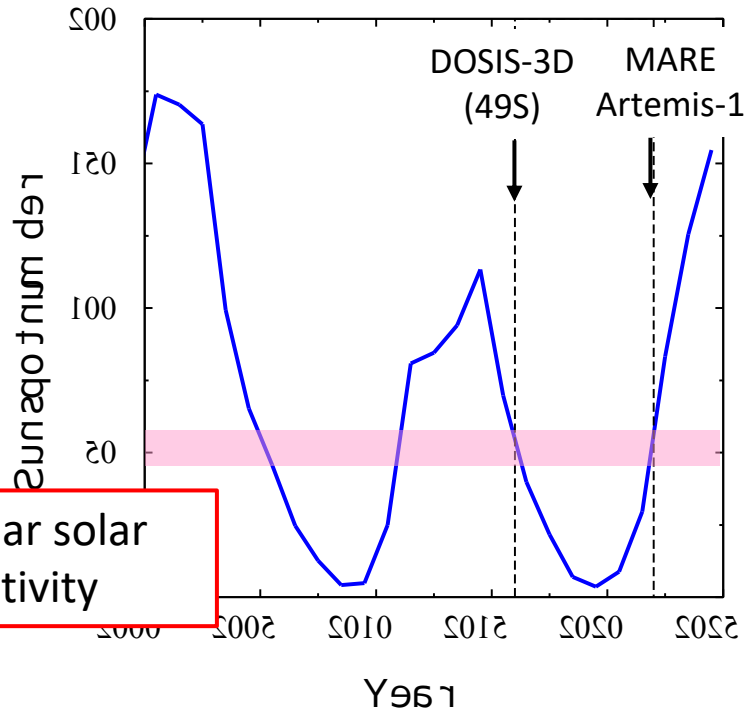
Inner and outer belts slightly contribute to dose exposure. This was subtracted using the NASA Hybrid Electronic Radiation Assessor dataset (George et al., Science 2024).

	D [mGy]	Q_{ICRP}	Q*
		H [mSv]	H [mSv]
OSLD+CR-39	12.3 ± 0.19	38.2 ± 1.34	37.7 ± 1.40
Subtraction	4.20 ± 0.45	5.31 ± 0.57	5.13 ± 0.55
	8.11 ± 0.49	32.9 ± 1.45	32.6 ± 1.50

LET spectra measured on the Orion and the ISS



Artemis-I MARE data showed higher fluxes due to weak geomagnetic field and thin shielding thickness

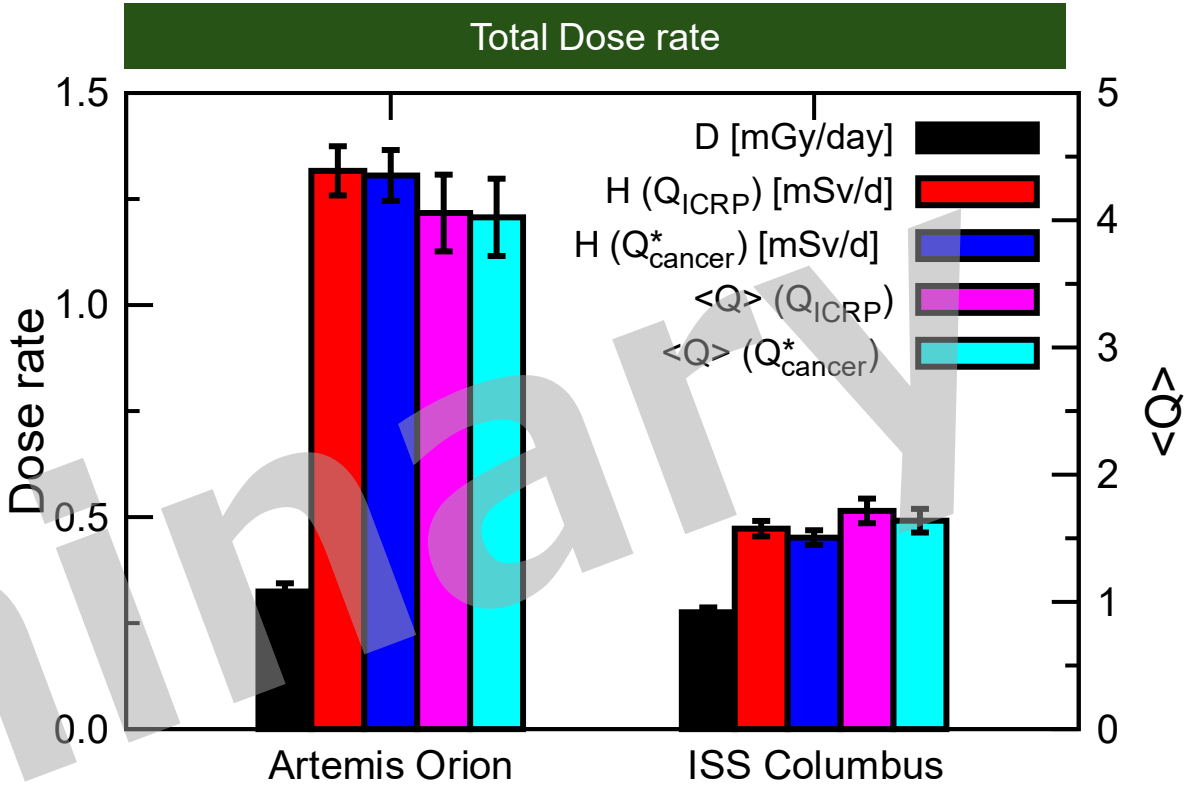


Similar solar activity

Dose equivalents were calculated using Q_{ICRP} and Q*, and subsequently compared.

Total dose rate

- Evaluation by the two quality factors did not present significant differences (~1.0% for Artemis-I Orion and ~3.5% for the ISS Columbus).
- Dose equivalent during the Earth-Moon cruise was about 2.5 times higher than that on the ISS.
- Mean quality factor was about 2 times larger.
  → Significant contributions from high LET HZE particles



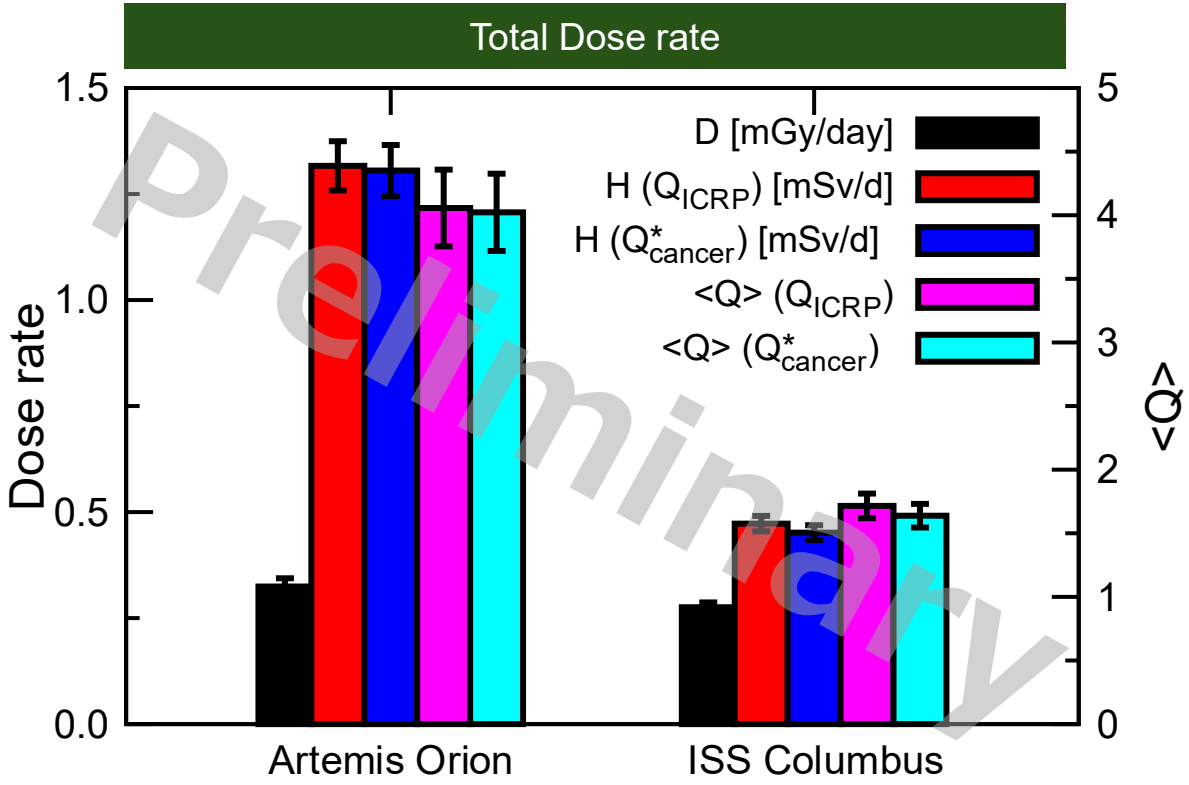
	D [mGy/d]	Q_{ICRP}		Q^*	
		H [mSv/d]	<Q>	H [mSv/d]	<Q>
MARE/Artemis-1 Orion	**0.32 ± 0.02**	**1.32 ± 0.06**	**4.06 ± 0.30**	**1.31 ± 0.06**	**4.02 ± 0.30**
DOSIS-3D/ISS Columbus module	0.28 ± 0.01	**0.47 ± 0.02**	**1.72 ± 0.10**	**0.45 ± 0.02**	**1.64 ± 0.09**

Preliminary

Summary

Dose measurements on the Artemis-I Orion and the ISS Columbus were compared combining with two different quality factors

- The Earth-Moon cruise data showed smaller contributions in the LET regions < 10 keV/μm and larger contributions in > 100 keV/μm.
  - ✓ Absence of trapped particles
  - ✓ Thin shielding environment
- The two quality factors, Q_{ICRP} and Q*, did not provide significant differences (~1.0% for Artemis Orion and ~3.5% for the ISS Columbus) beyond the measurement uncertainty.



Thank you for your kind attention

Děkuji vám