Study of the radiation environment on the surface of the lunar far side from Chang'E-4 mission

Pengwei Luo
Macau University of Science and Technology
2022-07-05@Zhuhai

Outline

- Basic knowledge of radiation and cosmic rays
- Chang'E-4 mission and Lunar Lander Neutrons and Dosimetry experiment (LND)
- LET and dose rate measurements
- Low-energy cosmic ray measurement
- Summary

Radiation

Ionizing radiation

- Beta radiation (β)
- Neutron radiation (n)
- Alpha radiation (α)
- Gamma radiation (γ)
- X-rays
- Ultraviolet radiation

$\lambda \uparrow$

Energy threshold: 10 eV, ionize atoms and molecules, and break chemical bonds.

Non-ionizing radiation

- Ultraviolet light (soft UV, from 3 eV to about 10 eV)
- Visible light
- Infrared
- Microwave
- Radio wave
- Very low frequency
- Extremely low frequency
- Thermal radiation (heat)
- Black-body radiation

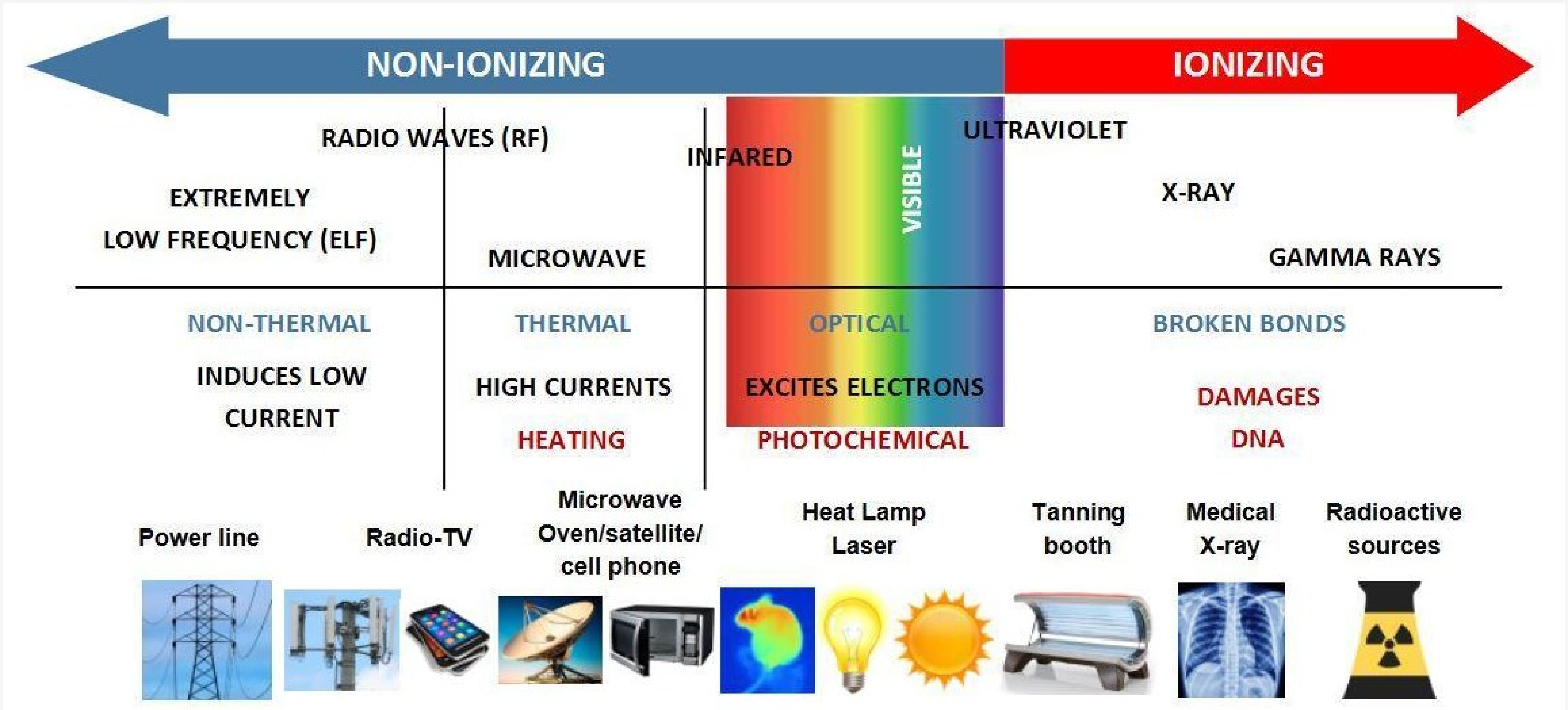
$\lambda \uparrow$

Wave-particle duality

$$E = h \cdot \nu = h \cdot \frac{2\pi}{\lambda}$$

E: particle's energy
h: Planck constant
v: frequency
λ: wavelength

Radiation



Credit: University of Washington

Radiation

- α (helium nuclei)

Charged

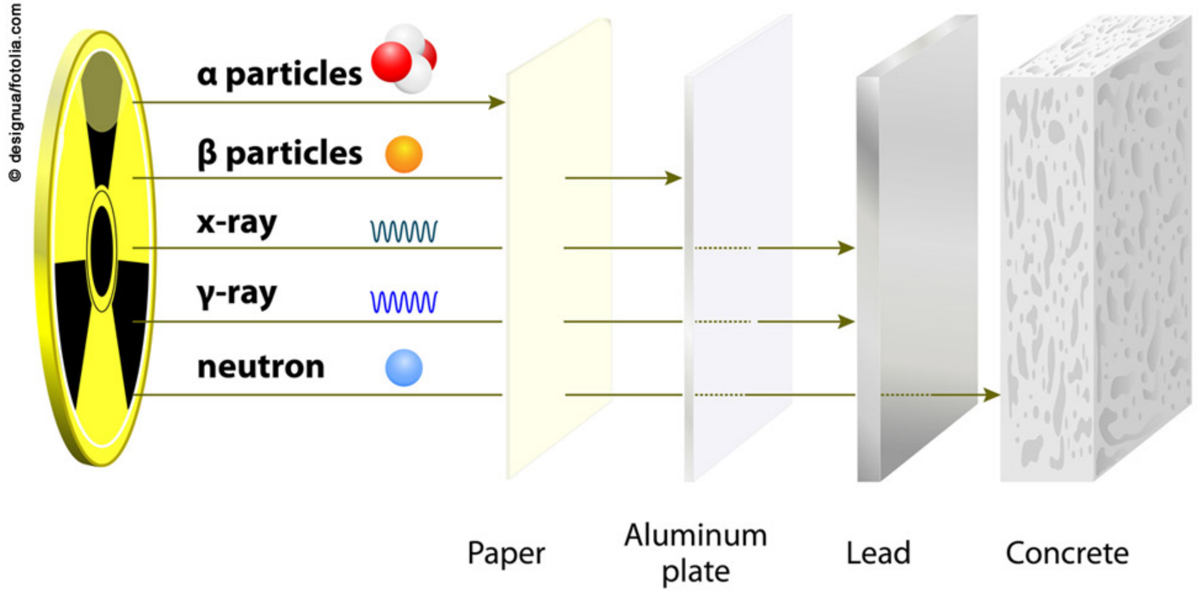
- β (electrons/positrons)
- x/γ (photons)

Neutral

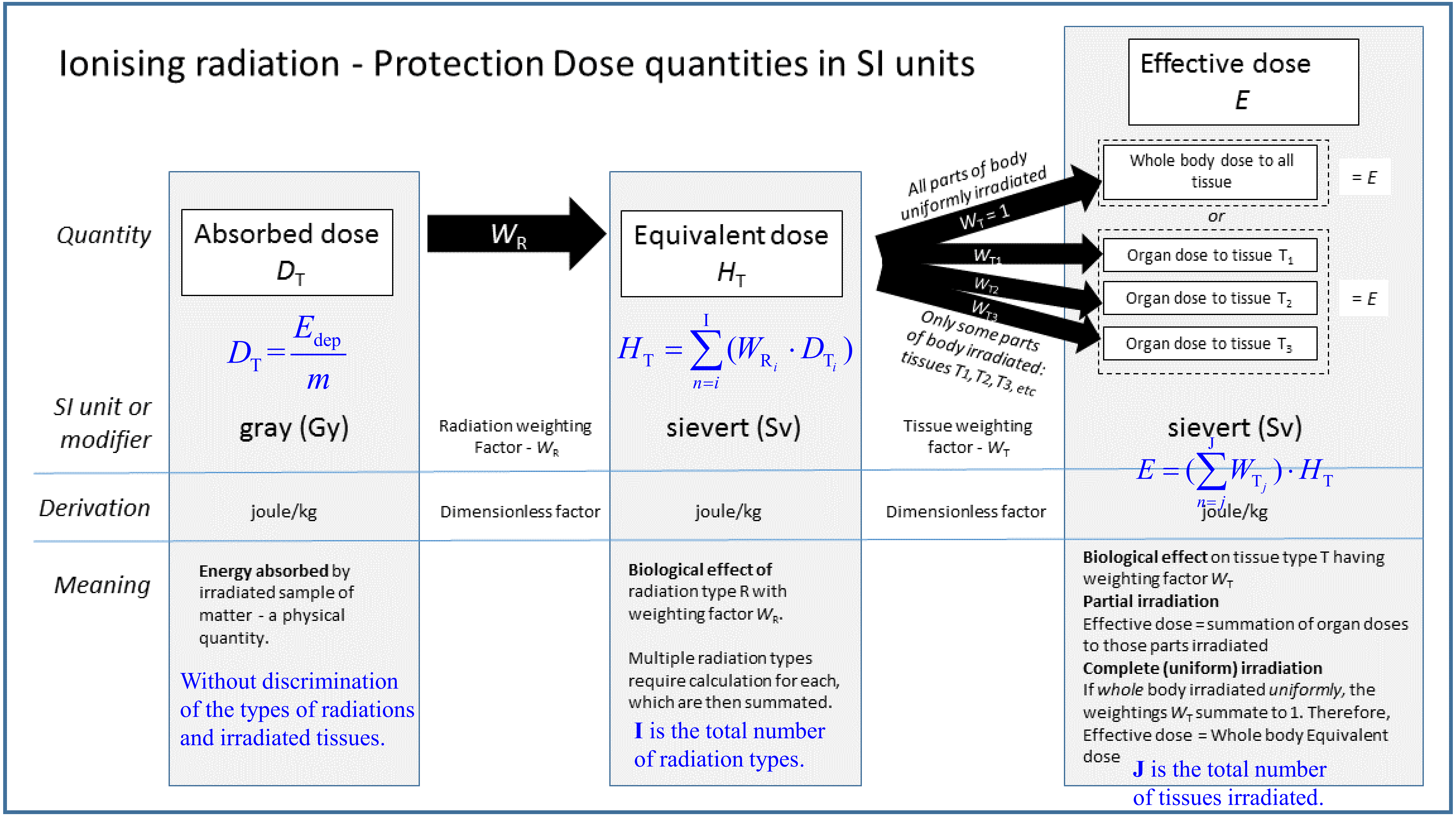
- n (free neutrons)

Unstable, τ = 877 s (~15 mins)

Penetrating power: α < β < x/γ
Ionization power: α > β > x/γ



Credit: Types of ionizing radiation



International System of Units (SI)

Radiation

Radiation weighting factors W_R used to represent relative biological effectiveness according to ICRP report 103

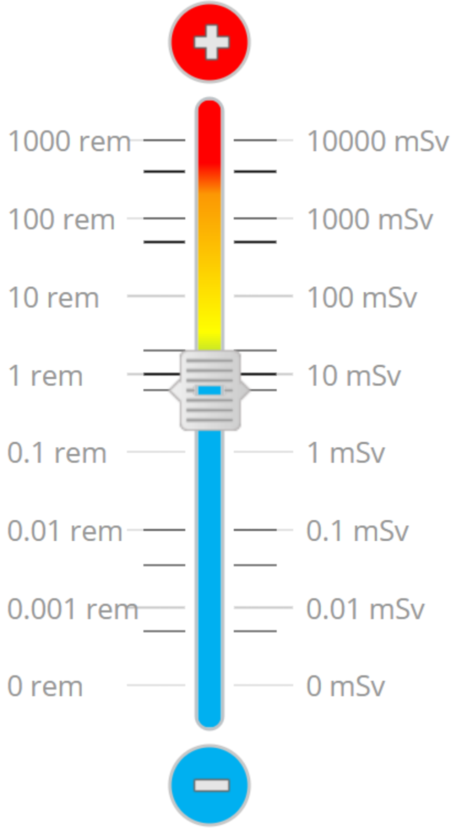
Radiation	Energy (E)	W_R (formerly Q)
x-rays, gamma rays, beta particles, muons		1
neutrons	< 1 MeV	$2.5 + 18.2 \cdot e^{-\frac{1}{6}\ln^2(E)}$
	1 – 50 MeV	$5.0 + 17.0 \cdot e^{-\frac{1}{6}\ln^2(2 \cdot E)}$
	> 50 MeV	$2.5 + 3.25 \cdot e^{-\frac{1}{6}\ln^2(0.04 \cdot E)}$
protons, charged pions		2
alpha particles, nuclear fission products, heavy nuclei		20

Weighting factors for different organs W_T

	Organs	Tissue weighting factors		
		ICRP26 1977	ICRP60 1990	ICRP103 2007
性腺	Gonads	0.25	0.20	0.08
红骨髓	Red bone marrow	0.12	0.12	0.12
结肠	Colon	—	0.12	0.12
	Lung	0.12	0.12	0.12
	Stomach	—	0.12	0.12
	Breasts	0.15	0.05	0.12
膀胱	Bladder	—	0.05	0.04
肝脏	Liver	—	0.05	0.04
食管	Oesophagus	—	0.05	0.04
甲状腺	Thyroid	0.03	0.05	0.04
	Skin	—	0.01	0.01
	Bone surface	0.03	0.01	0.01
唾腺	Salivary glands	—	—	0.01
	Brain	—	—	0.01
	Remainder of body	0.30	0.05	0.12
	Total	**1.00**	**1.00**	**1.00**

Radiation

Choose A Dose

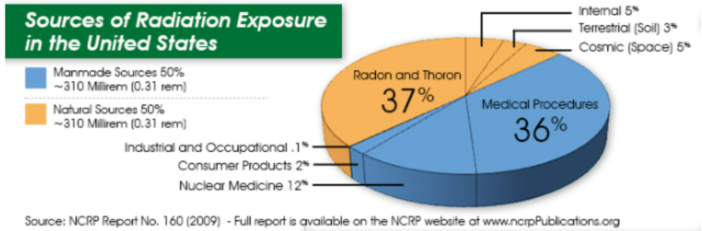


Example Of Exposure At This Dose

Select One:

Average Annual Dose in the U.S.

Text Version

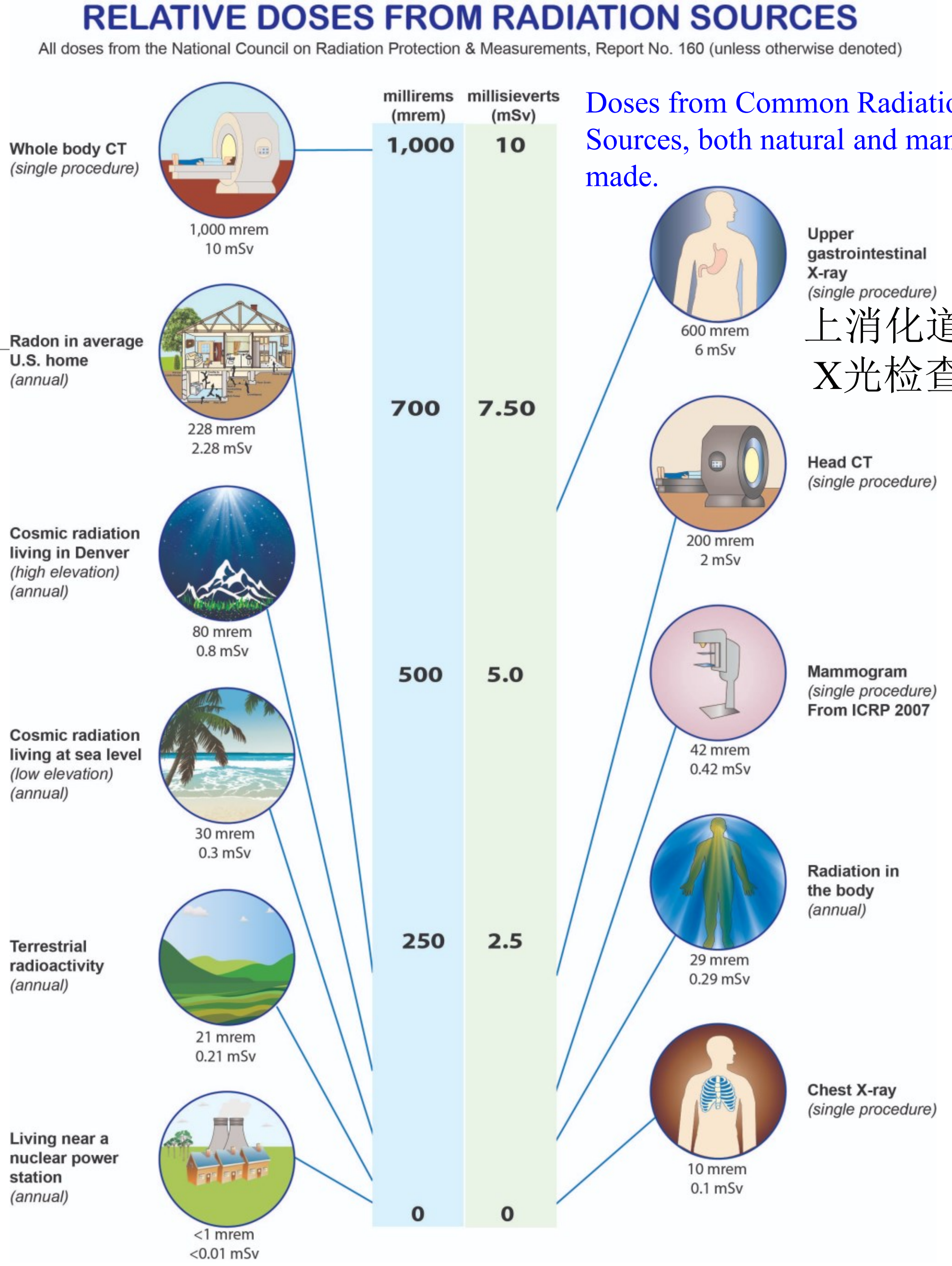


0.62 rem / 6.2 mSv

Average dose per year for people in the U.S.[3] from:

- naturally occurring background radiation – 310 mrem
- medical exposures – 300 mrem
- consumer products – 10 mrem

Credit: CDC Radiation Emergencies | Radiation Thermometer



Doses from Common Radiation Sources, both natural and man-made.

上消化道 X光检查

Data Points

Credit: CDC Radiation Emergencies | Radiation Thermometer Text Version

Rem (rem)	Millisievert (mSv)	DESCRIPTOR
1000	10,000	Dose that results in death for 100% of those who receive it.[1] People who are close to the site of a radiation emergency may be at risk for this dose.
400	4,000	Dose that results in death for 50% of those who receive it.[1] People who are close to the site of a radiation emergency may be at risk for this dose.
100	1,000	Lowest dose that could cause acute radiation syndrome.[1] Dose for which risk of getting a fatal cancer increases from about 22% (average risk of cancer in United States) to about 27%.[derived from [2]]
50	500	Dose that causes damage to blood cells.[6,7]
2	20	Recommended threshold for relocating people (if projected dose from radioactive contamination is greater for the coming year, relocate).[8]
1	10	Dose received during a typical CT (Computerized Tomography) scan.[3]
0.62	6.2	Average dose per year for people in the U.S.[3] from: • naturally occurring background radiation – 310 mrem • medical exposures – 300 mrem • consumer products – 10 mrem
0.01	0.1	Typical dose from a chest x-ray.[3]
0.0035	0.035	Dose from high altitude solar and cosmic radiation during a flight from New York City to Los Angeles.[derived from [9]]
0.0005	0.005	Typical dose from a dental x-ray (bitewing and full mouth survey).[5]

Radiation

Earth-Moon system

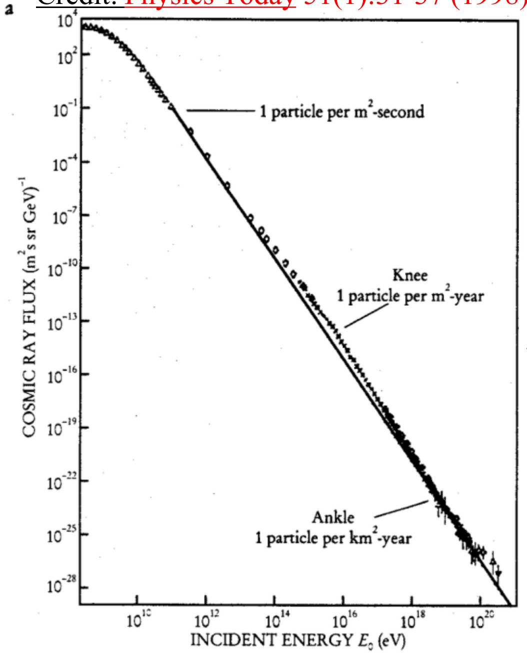
Comparison of the surface radiation environments on the Moon and the Earth

Celestial body	**Earth**	**Moon**
Surface environment	➢ Dense atmosphere ➢ Stable global dipole magnetic field	➢ Without a substantial atmosphere ➢ Without global magnetic field
Main radiation source	Gamma rays and low-energy alpha particle (Radioactive elements in our living environment)	Ions of high atomic number and energy (**Cosmic rays** and the secondary particles produced by their interactions with the lunar surface)

Credit: Rev. Mod. Phys. **83**, 1245 (2011)

Cosmic rays

Credit: Physics Today 51(1):31-37 (1998)

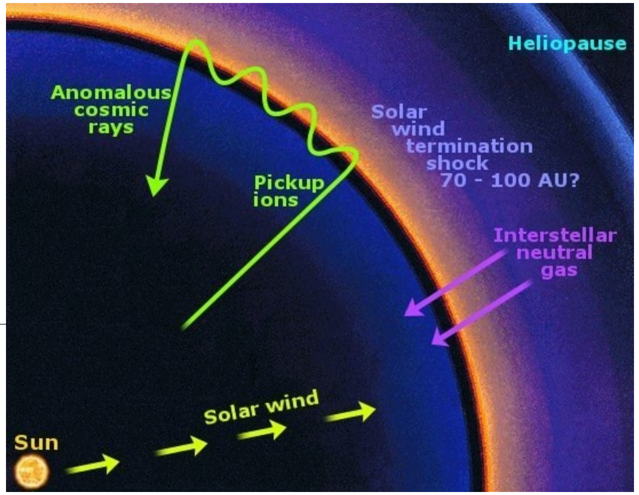


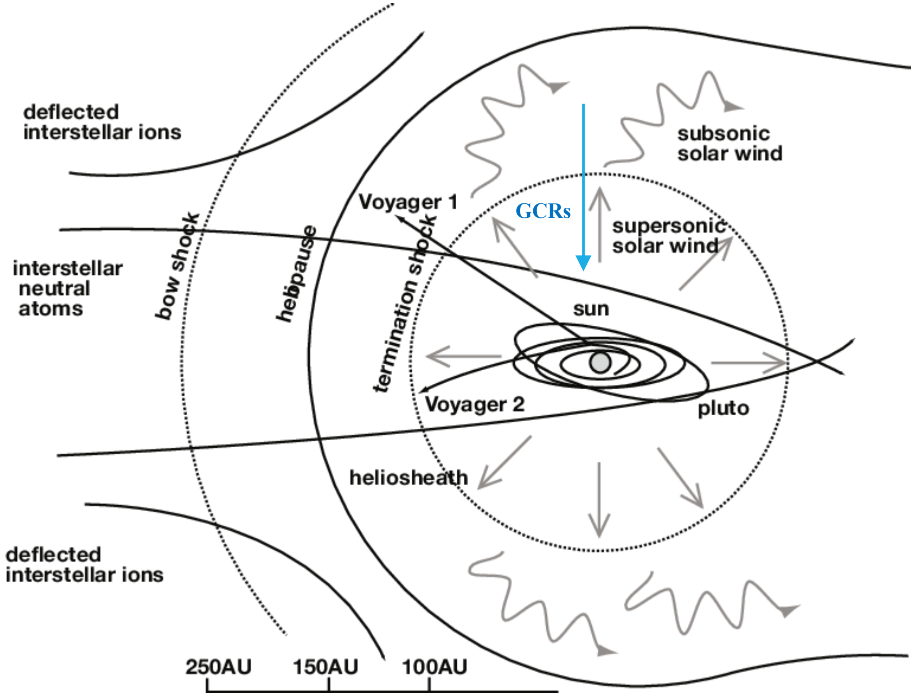
Types

- Solar energetic particles (SEPs): originate from the Sun, associated with intense solar activities (such as solar flare and CME).
- Galactic cosmic rays (**GCRs**): from the explosions of supernovae within our own Milky Way Galaxy;
- Anomalous cosmic rays (ACRs): from neutral atoms of the local interstellar medium (H, He, N, O, Ne, and Ar, elements with high FIPs).

Inner heliosphere: < 1 AU from the Sun

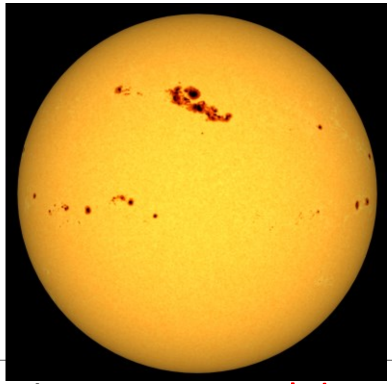
Heliosphere



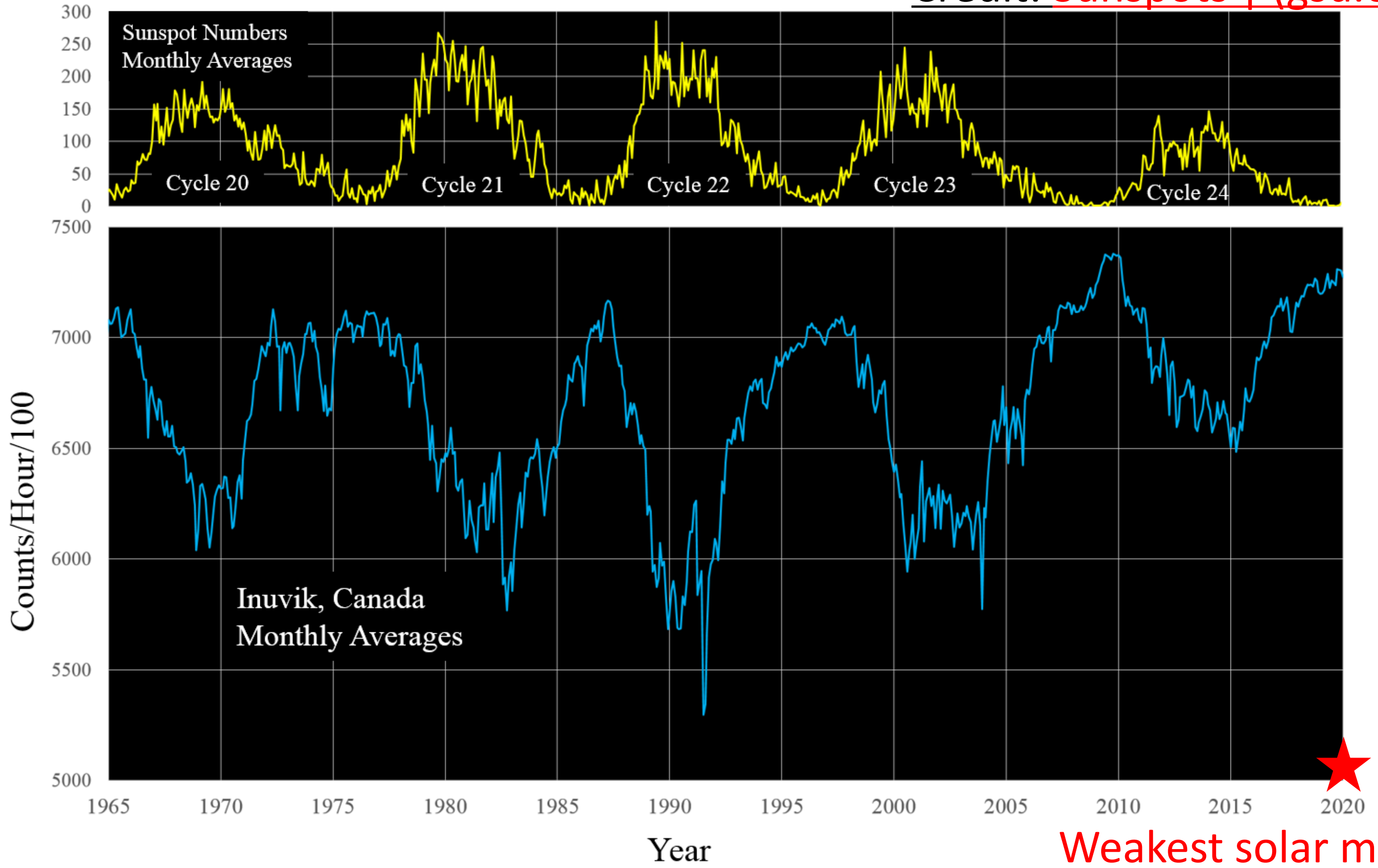


Schematic drawing of the heliospheric interface

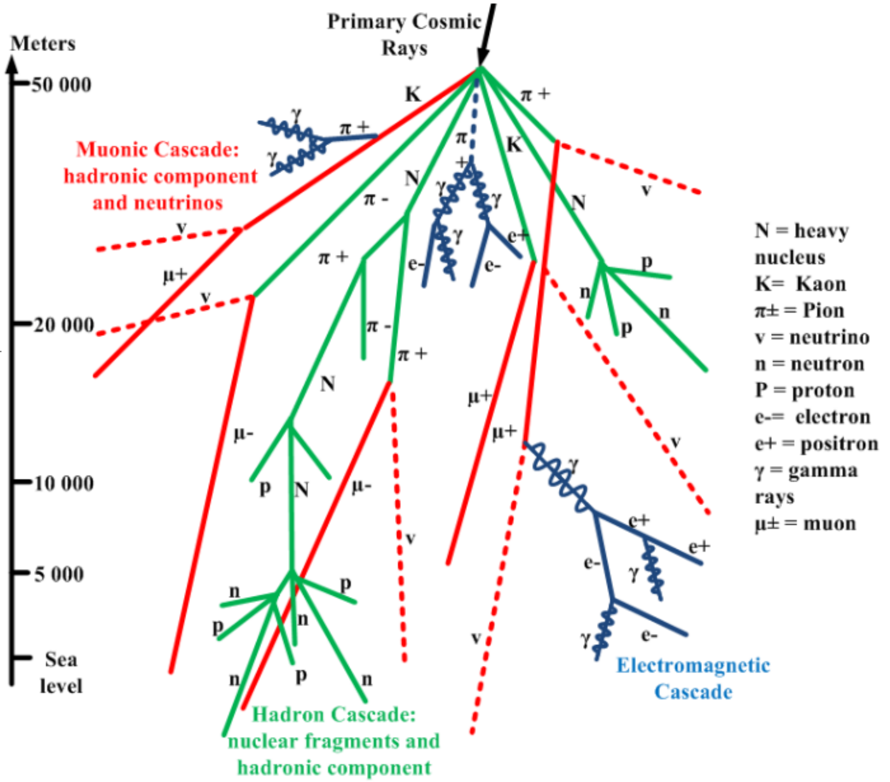
Cosmic rays



Credit: Sunspots | (gsu.edu)



Weakest solar minimum



Credit: Showers of cosmic ray reactions with particles of the atmosphere

Solar modulation refers to the influence the Sun exerts upon the intensity of galactic cosmic rays. As solar activity rises (top panel, Source: WDC-SILSO Royal Observatory of Belgium, Brussels), the count rate recorded by a neutron monitor in Inuvik, Canada decreases (bottom panel, Source: Bartol Research Institute, University of Delaware, USA).

Credit: Solar Modulation (udel.edu)

Chang’E-4 mission and LND

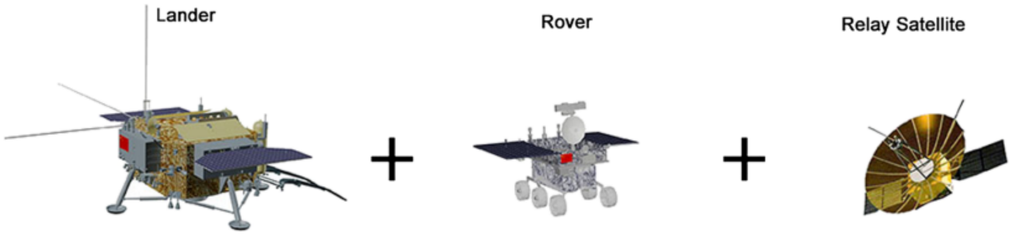
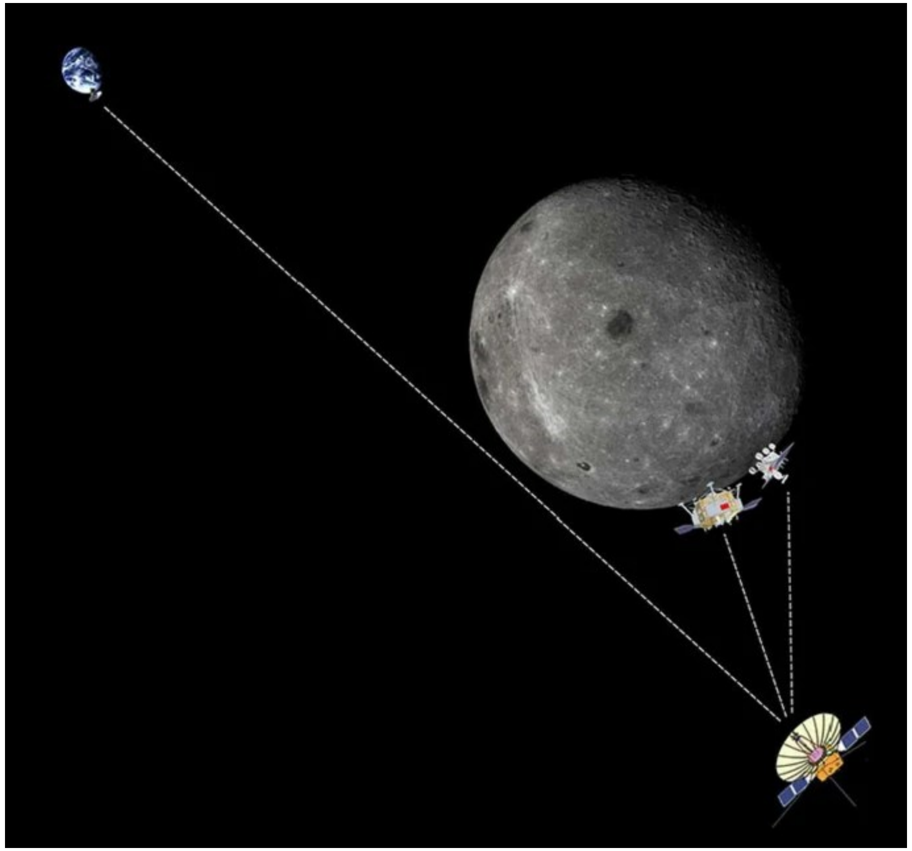


Fig. 2 The schematic diagram of the CE-4 probe components



Credit: Space Sci. Rev. 217, 35 (2021)

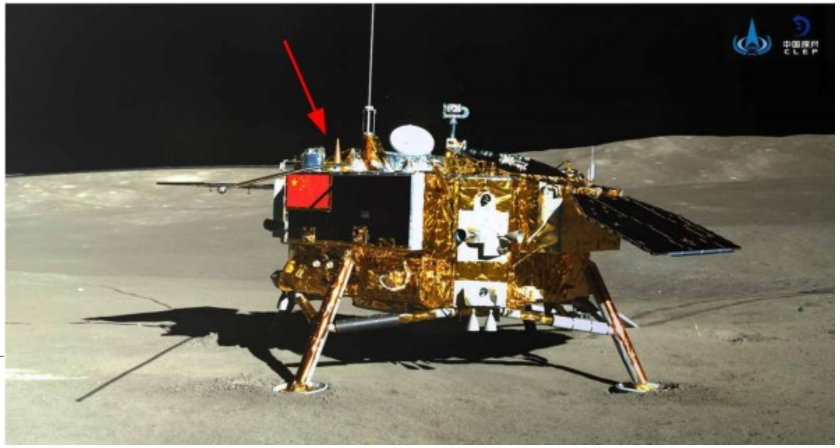
- Launch time: December 8, 2018
- Landing time: 10:26 (UTC+8) January 3, 2019
- Landing site: Von Kármán crater (45.5° S, 177.6° E) at the surface of the lunar far side
- Payload: Four instruments onboard the lander (CE-4) and the rover (Yutu-2), respectively
- Current status: Alive

Chang'E-4 mission and LND

Table 2 The CE-4 science objectives and corresponding instruments capabilities

Science objective	Science exploration tasks	Contributing instruments		
		Lander instruments	Rover instruments	Relay satellite instrument
Low-frequency radio astronomical observation	Detect the solar low frequency radio radiation (0.1∼40 MHz) Detect the low frequency radio radiation from other celestial body in solar system and galaxy (0.1∼80 MHz)	Low-Frequency Radio Spectrometer (LFRS)		Netherlands-China Low frequency Explorer (NCLE)
Geomorphology, mineral compositions, shallow subsurface structure of and near the landing area	3D imagery In-situ analysis of chemical composition (element content and distribution) In-situ analysis of mineral compositions (mineralogical content and distribution) Regolith thickness and shallow subsurface structure	Landing Camera (LCAM) Terrain Camera (TCAM)	The Panoramic Camera (PCAM) VIS-NIR Imaging Spectrometer (VNIS) Lunar Penetrating Radar (LPR)	
Experimentally detect the lunar environment at far side of the lunar, such as dosage neutron, neutral atom	Measure the electrically neutral component, neutrons and γ-rays. Measure the fast neutron flux and thermal neutrons flux In-situ analysis of energy neutral atom and cation	Lunar Lander Neutrons & Dosimetry (LND)	Advance Small Analyzer for Neutrals (ASAN)	

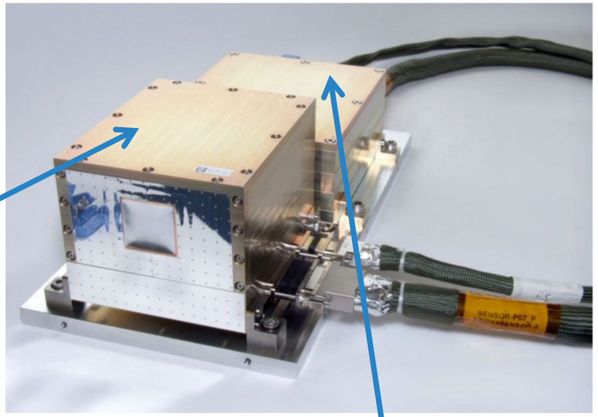
Credit: Space Sci. Rev. 217, 35 (2021)



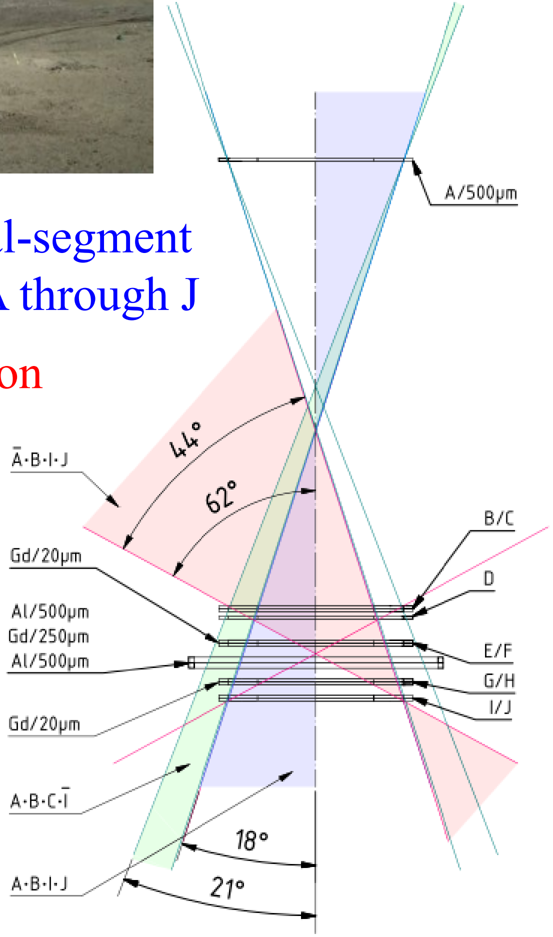
A stack of ten 500-μm-thick dual-segment Si solid-state detectors labeled A through J

Telescope configuration

Sensor Head



Electronic Box



Credit: Space Sci. Rev. 216, 104 (2020)

Chang'E-4 mission and LND

Reasons for lunar surface radiation environment study

- Safety concerns relating to exposure to space radiation (Astronaut and instrument)
- Manufacturing costs control due to severe mass constraints in spaceflight

Influencing factors of lunar radiation environment

- Lunar exosphere
- Dust grains
- Lunar magnetic anomalies
- Solar wind reflected particles
- Local terrain obscuring
- Secondary particles produced by the interactions between CRs and the nuclei of lunar regolith

LET and dose rate measurements

SCIENCE ADVANCES | RESEARCH ARTICLE

PLANETARY SCIENCE

First measurements of the radiation dose on the lunar surface

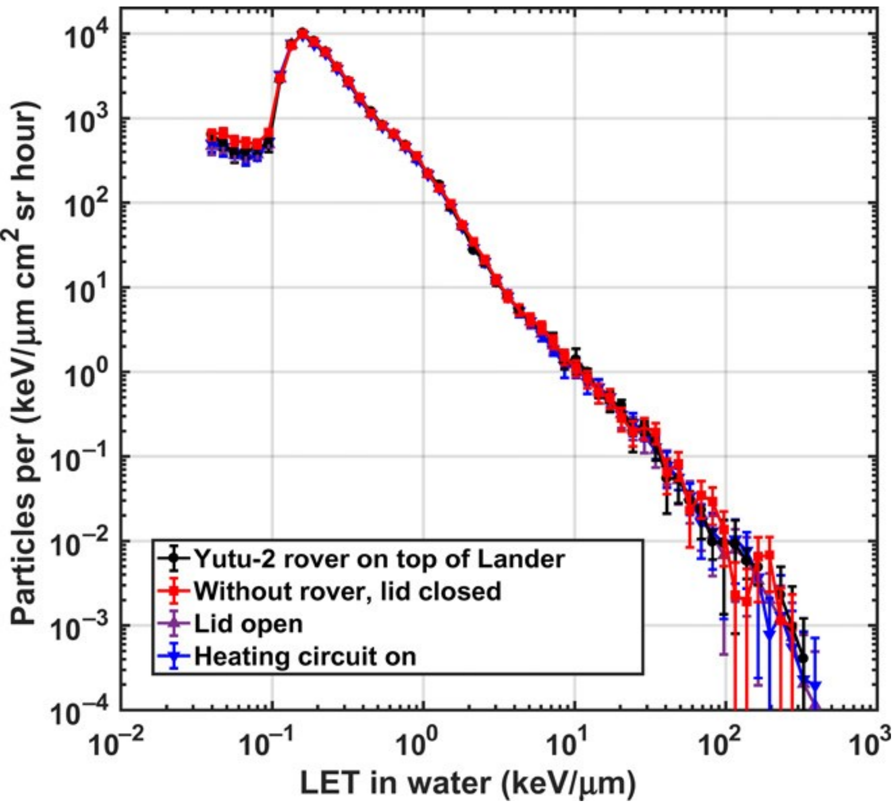
Shenyi Zhang[1,2,3,4], Robert F. Wimmer-Schweingruber[1,5]*, Jia Yu[5]†, Chi Wang[1], Qiang Fu[6,7], Yongliao Zou[1], Yueqiang Sun[1,2,4], Chunqin Wang[1,2,4], Donghui Hou[1,2,3,4], Stephan I. Böttcher[5], Sönke Burmeister[5], Lars Seimetz[5], Björn Schuster[5], Violetta Knierim[5], Guohong Shen[1,2,4], Bin Yuan[1,2,4], Henning Lohf[5], Jingnan Guo[5,8,9], Zigong Xu[5], Johan L. Freiherr von Forstner[5], Shrinivasrao R. Kulkarni[5], Haitao Xu[1], Changbin Xue[1], Jun Li[1], Zhe Zhang[10], He Zhang[11], Thomas Berger[12], Daniel Matthiä[12], Christine E. Hellweg[12], Xufeng Hou[13], Jinbin Cao[14], Zhen Chang[1,2,4], Binquan Zhang[1,2,4], Yuesong Chen[1], Hao Geng[1], Zida Quan[1,2,4]

- **Research contents**

➢ Measure the linear energy transfer spectrum on the lunar surface;

➢ Measure the dose rate on the lunar surface (charged + neutral particles).

LET and dose rate measurements



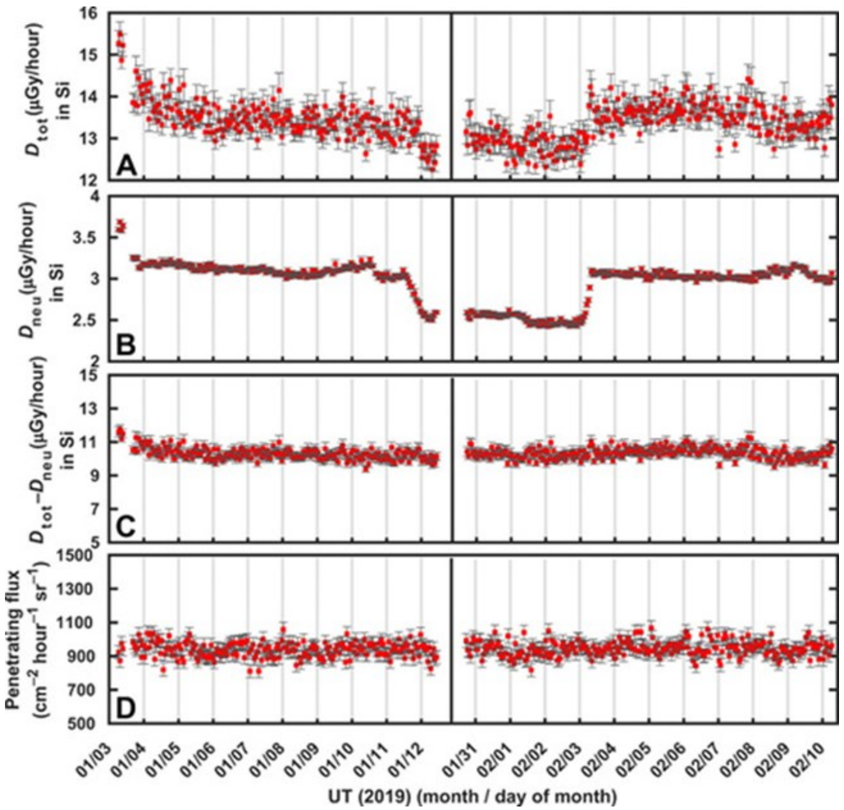


Table 1. Summary of measurements of the radiation dose rate measured in µGy/hour on the lunar surface. The errors of the background dose rate from the RTG/RHUs (20) are considered systematic errors and have been added quadratically when reporting the final values in the rightmost column.

Dose rate (µGy/hour)	Measured	Background	Final in Si
Total	18.4 ± 0.4	5.2 ± 0.6	13.2 ± 0.7
Neutral	4.7 ± 0.1	1.7 ± 0.5	3.1 ± 0.5
Charged	13.7 ± 0.4	3.5 ± 0.8	10.2 ± 0.9

- Consistent with that measured by LRO/CRaTER (10.0 µGy/hour) for charged particles
- Contribution from neutral particles are non-negligible (23±4)%
- GCR equivalent dose rate: (57.1 ± 10.6) µSv/hour

Average quality factor: **<Q>**=4.3±0.7

Low-energy cosmic ray measurements

SCIENCE ADVANCES | RESEARCH ARTICLE

SPACE SCIENCES

First measurements of low-energy cosmic rays on the surface of the lunar farside from Chang'E-4 mission

Pengwei Luo[1,2], Xiaoping Zhang[1,2]*, Shuai Fu[1,2], Yong Li[1,2], Cunhui Li[3], Jinbin Cao[4]

- **Research contents**

- Measure the low-energy cosmic ray (CR) energy spectra on the lunar surface (H, He, CNO, and HI);
- Extract the ratios of ^{3}He to ^{4}He;
- Verify the dawn-dusk symmetry of the CR energy spectrum on the lunar surface.

Low-energy cosmic ray measurements

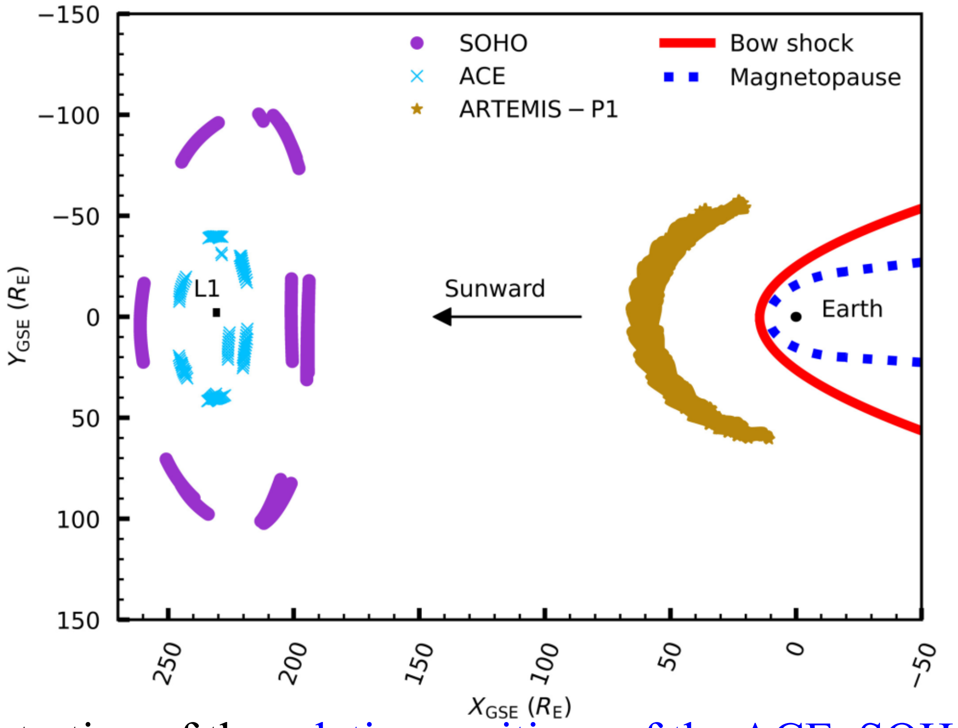
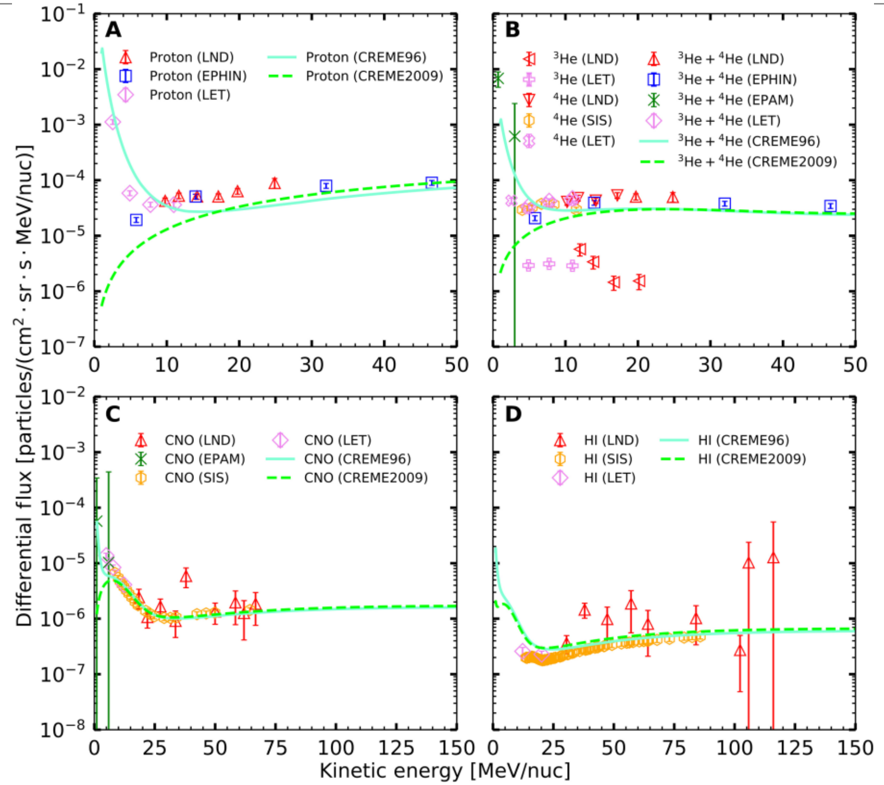
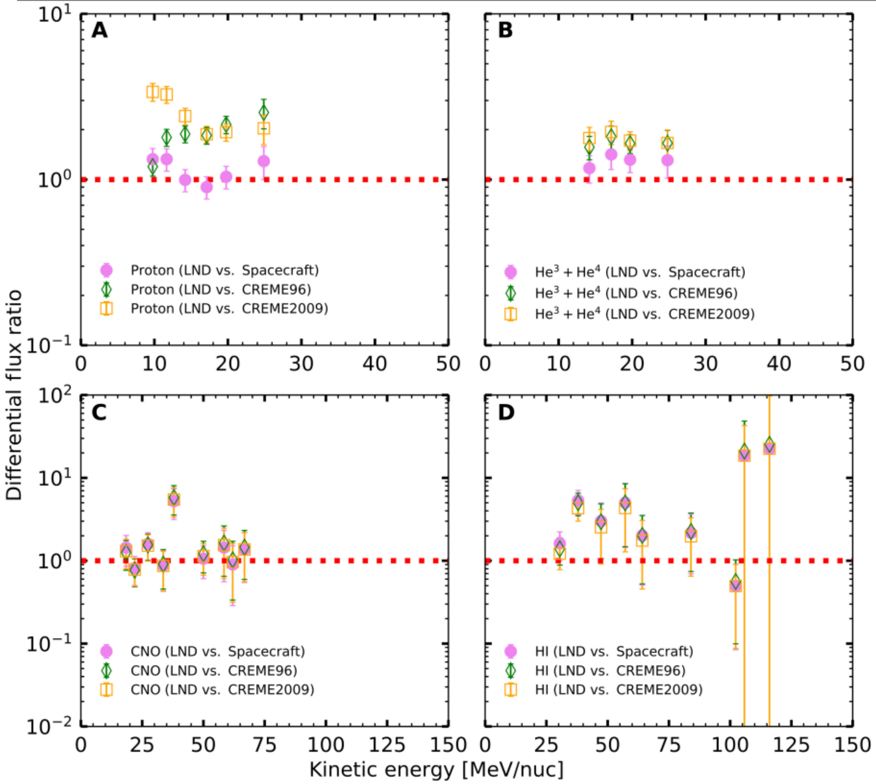


Illustration of the relative positions of the ACE, SOHO, and ARTEMIS-P1 spacecraft in the X-Y GSE plane during the working periods of the CE-4/LND.

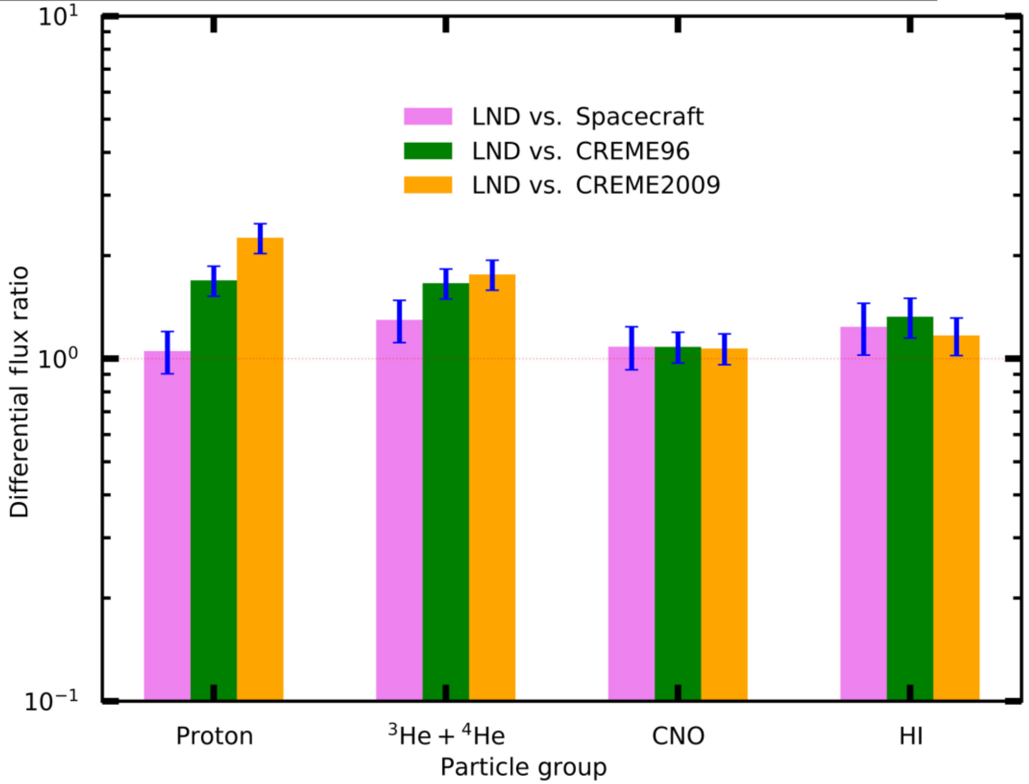


Comparisons of the CR fluxes between the CE-4/LND measurements and the in situ measurements made at 1 AU and the predictions of the CRÈME models.

Low-energy cosmic ray measurements

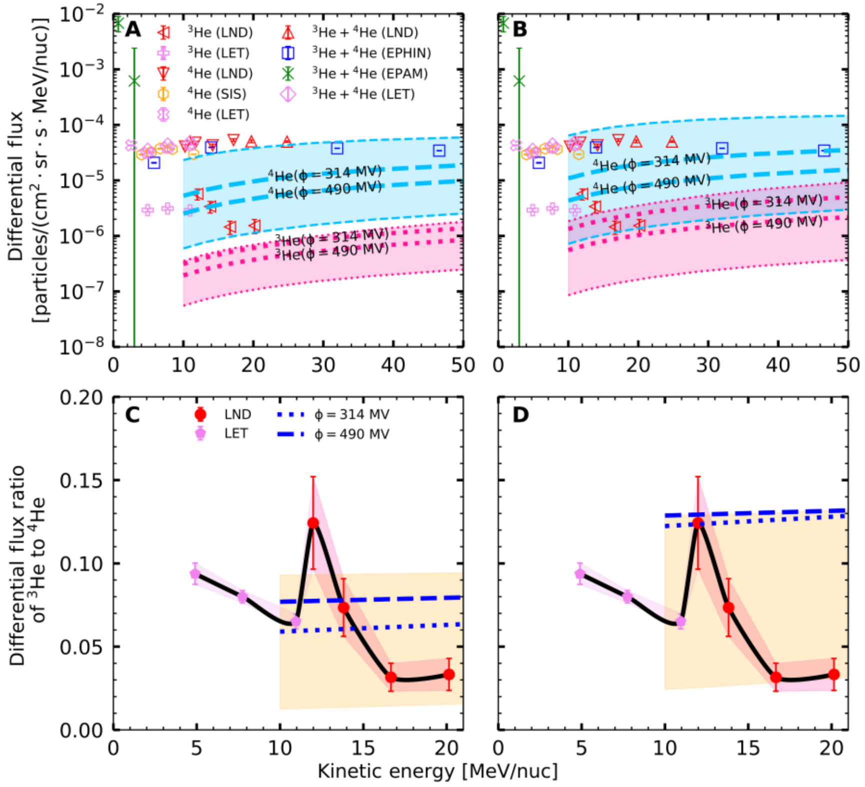


CR flux ratios of the CE-4/LND measurements to the in situ measurements made at 1 AU and to the CRÈME modeling results.

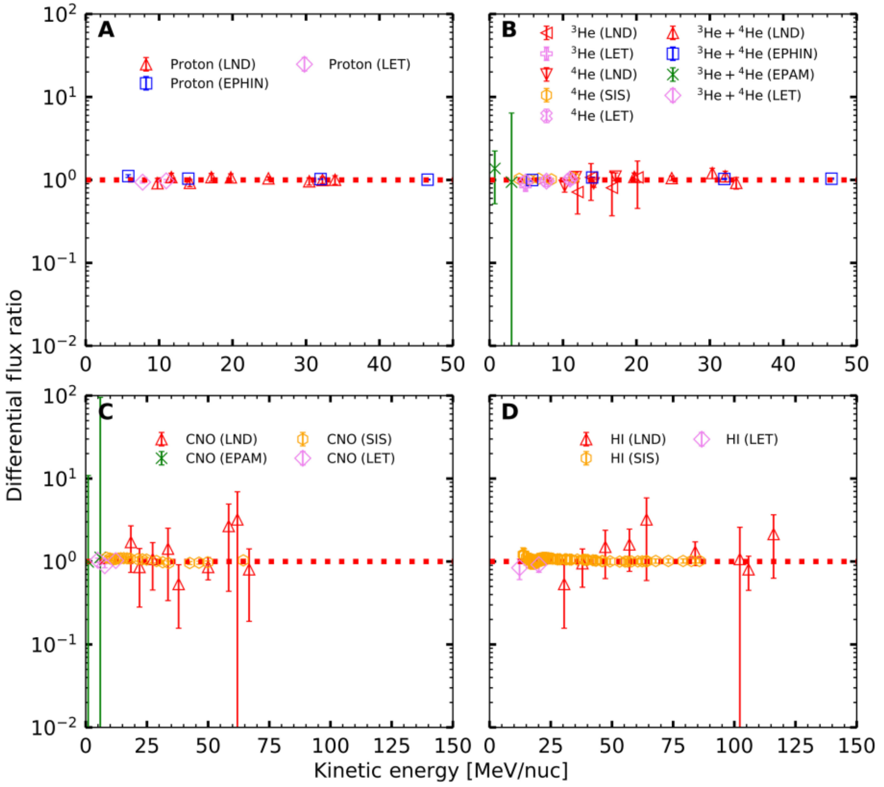


Similar to the figure on the left, but are averaged over the energies of each group.

Low-energy cosmic ray measurements



The CR energy spectra of ^{3}He and ^{4}He and the ratios of ^{3}He to ^{4}He.



The ratios of the observed CR fluxes in the lunar local morning to those in the lunar local afternoon.

Low-energy cosmic ray measurements

- **Research significance**
- Verify the related theoretical models;
- Provide input data for CR and CR-related studies on the lunar surface, enhancing our understanding on the proton, neutron, and gamma emission spectroscopy from the lunar surface;
- Confirmation of the CR dawn-dusk symmetry on the lunar surface guides the selections of landing times for future crewed lunar missions and extravehicular activities on the lunar surface.

Summary

- **Radiation (type, absorbed dose, equivalent dose, effective dose, and radiation sources in daily lives)**

- **Cosmic rays (type, origination, and solar modulation)**

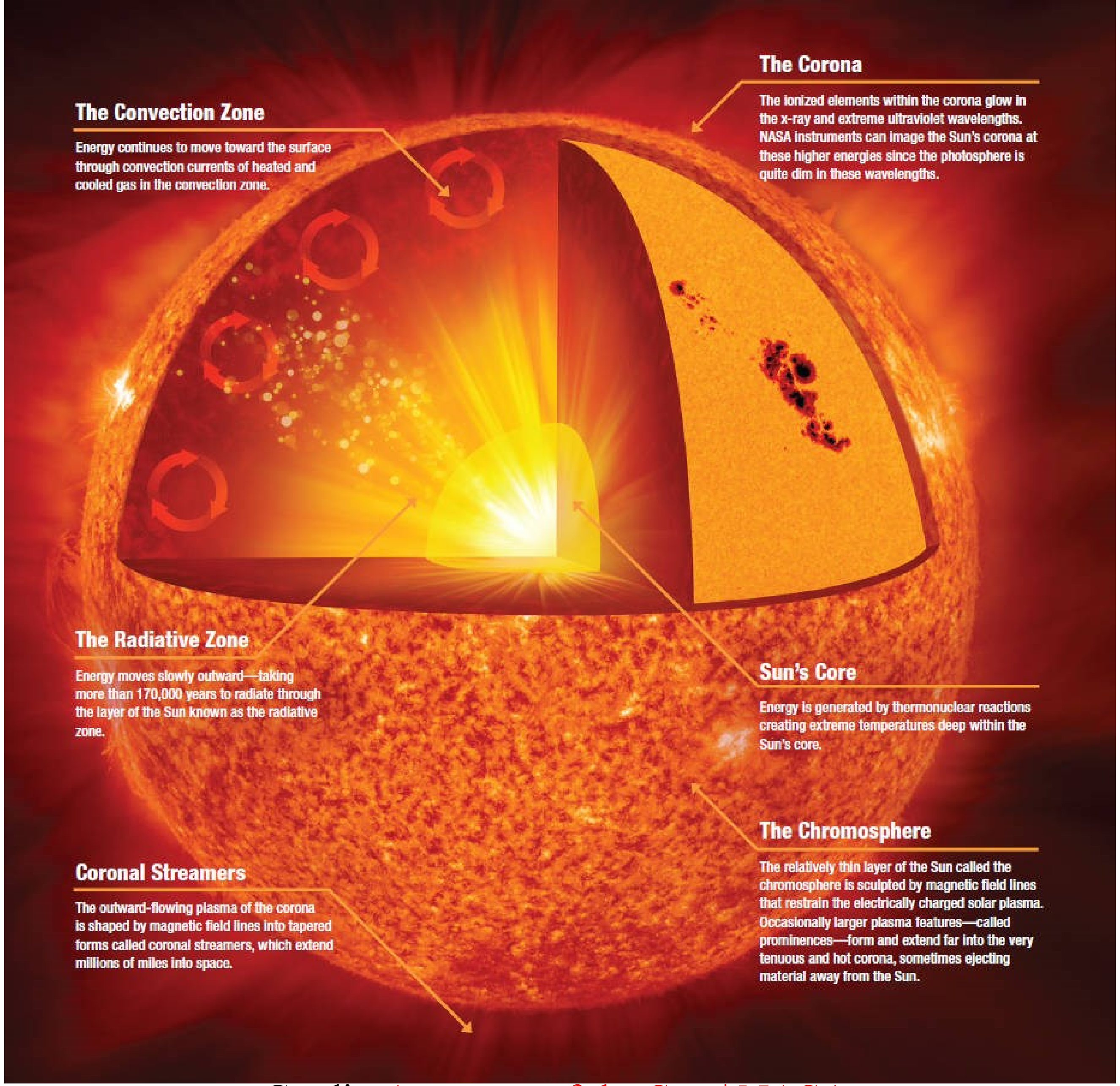
- **Chang'E-4 mission and the LND**

- **Radiation dose rate and LET spectrum (absorbed dose rate and equivalent dose rate in water from the charged and neutral particles)**

- **Cosmic rays measurements (energy spectrum, flux ratios of ^{3}He to ^{4}He, and dawn-dusk symmetry of the CR energy spectrum verification)**

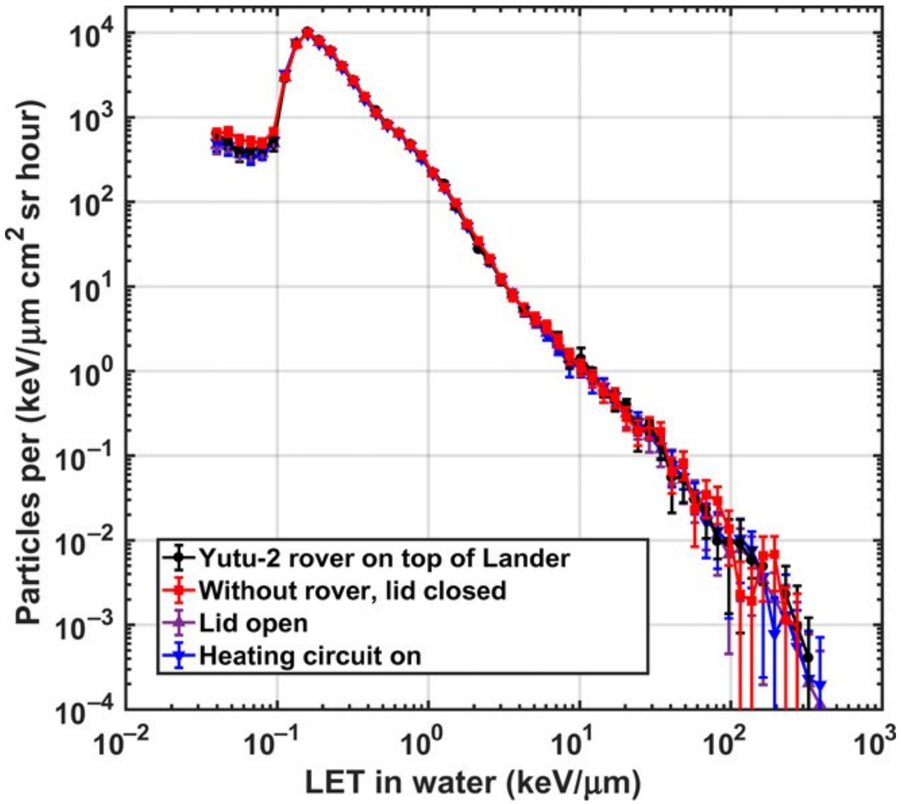
Thank you for your attention!

Backup



Credit: Anatomy of the Sun | NASA

LET and absorbed dose rate measurement



[ICRP, 1991]

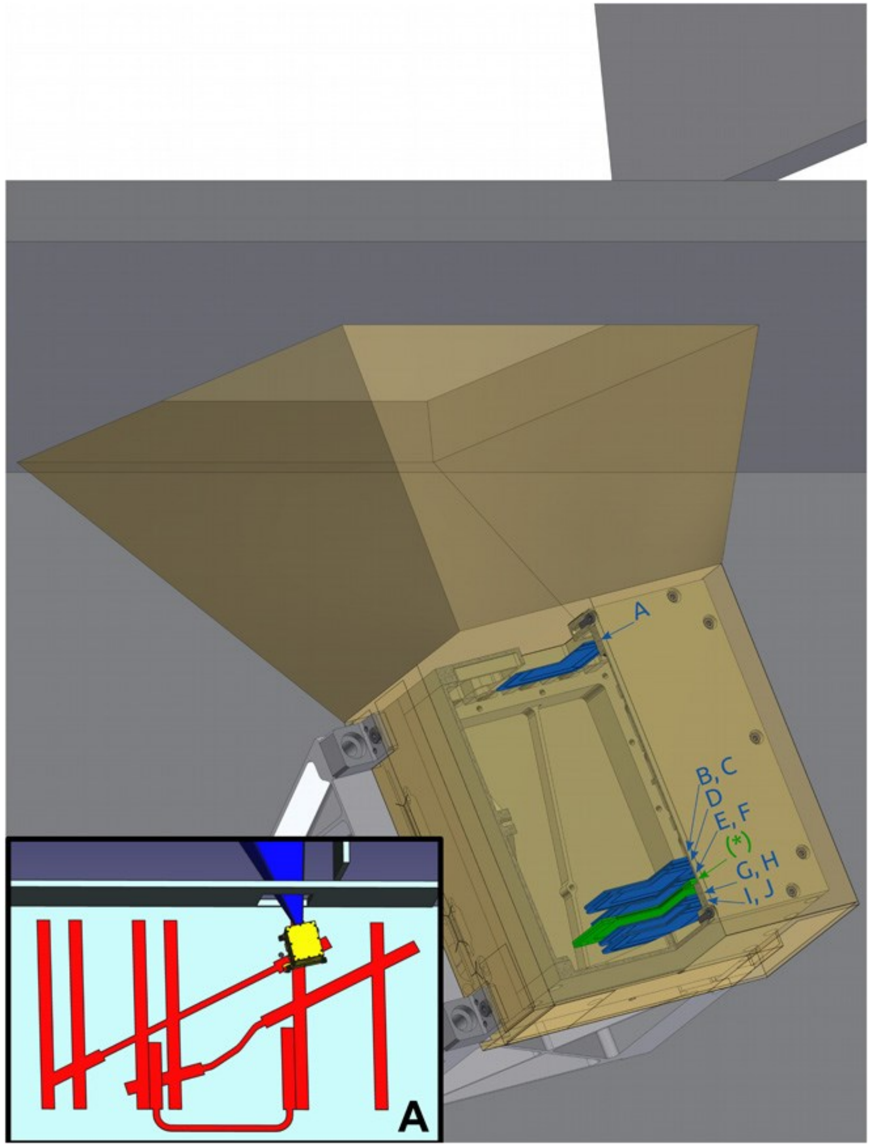
$Q = 1.0$ $L < 10$ keV/µm

$Q = 0.32\,L - 2.2$ $10 \le L \le 100$ keV/µm

$Q = 300/(L)^{1/2}$ $L \ge 100$ keV/µm

L = 水中的非限定LET (keV/ µm)

Average quality factor: **<Q>**=4.3±0.7



Schematic view of the LND sensor head and its accommodation in the Chang'E 4 payload compartment.

The LND detector system consists of 10 dual-segment silicon SSDs (A to J) shown and labeled in blue. They are arranged such as to form a particle telescope that views the sky through an opening of the payload compartment. The structure shown in green absorbs thermal neutrons and is irrelevant for this paper. This opening in the payload compartment (indicated by gray walls) is closed during the lunar night and reopened in the lunar morning. Multilayer insulation is shown in gold and insulates the LND sensor head, which is mounted to the side panel of the payload compartment with an Al bracket also shown in gray. Inset A shows LND's location on the payload panel (in pale blue) together with its NH3 thermal control system (TCS) indicated in red.