FIVE YEARS OF RADIATION MEASURMENTS ON THE FAR SIDE OF THE MOON – RESULTS FROM THE LUNAR LANDER NEUTRON AND DOSIMETRY EXPERIMENT ON CHANG'E 4.

R. F. Wimmer-Schweingruber[1,2], S. Zhang[2,3,4], L. Yang[1], Z. Xu[5], T. Berger[6], and S. I. Böttcher[1], [1]Institute of Experimental and Applied Physics, Kiel University, Leibnizstrasse 11, 24118 Kiel, Germany, wimmer@physik.uni-kiel.de, [2]National Space Science Center, Chinese Academy of Sciences, Beijing, PR China, [3]Beijing Key Laboratory of Space Environment Exploration, Beijing, PR China, [4]University of Chinese Academy of Science, Beijing, PR China, [5]California Institute of Technology, Pasadena, California, USA, [6]German Aerospace Center (DLR), Institute of Aerospace Medicine, Cologne, Germany

Introduction: Human exploration of the Moon is associated with substantial risks to astronauts from space radiation. On the surface of the Moon, this consists of the chronic exposure to galactic cosmic rays and sporadic solar particle events. The interaction of this radiation field with the lunar soil leads to a third component that consists of neutral particles, i.e., neutrons and gamma radiation. We report on five years worth of radiation measurements acquired by the Lunar Lander Neutron and Dosimetry (LND) experiment [1] aboard the Chinese lunar lander Chang'E 4 and describe the instrument. First results were reported by [2], here we will provide an update to reflect rising solar activity.

Instrument Description: LND, shown in Fig. 1, consists of a stack of 10 Si-solid-state detectors A-J which together form a particle telescope shown in Fig. 2. The sensor head (front in Fig. 1) faces the cold sky through an opening of the lander deck, the electronics box is accommodated in the lander. All detectors have an inner and an outer segment. Detectors BCD are placed closely together so that B, D and the outer segment of C act as anti-coincidence for the measurement of neutral dose in the inner C segment. Detector pairs EF and GH sandwich a thin Gd foil that allows measurement of thermal neutrons.

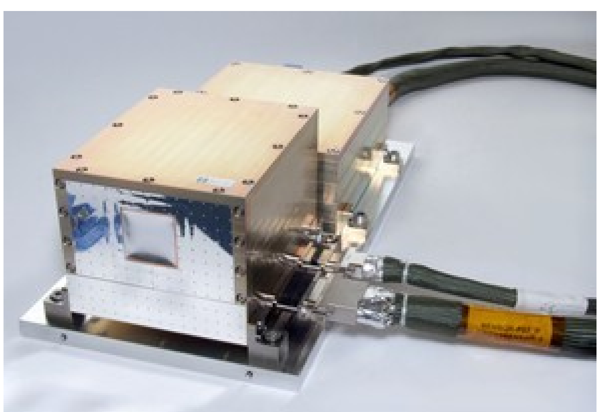

Figure 1: The Lunar Lander Neutron and Dosimetry (LND) Experiment consists of the sensor head (front) and electronics box (rear) which are connected by a power and data harness. From [1].

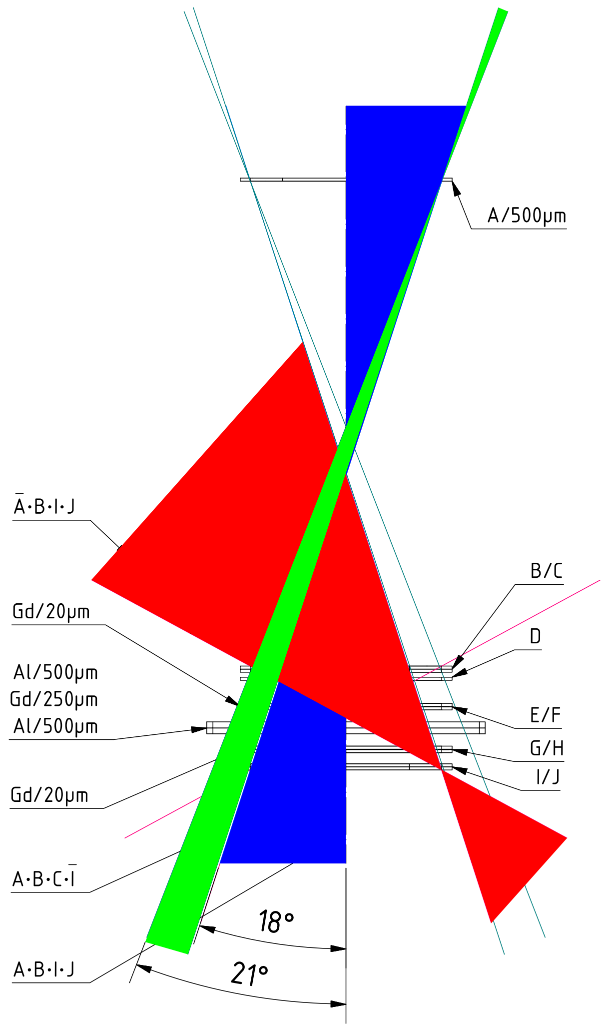

Figure 2: LND consists of 10 Si solid-state detectors which form a particle telescope. Adapted from [1].

Measurements: LND is switched off and covered by a lid during the local night but provides several distinct measurements during the local day time:

High time resolution. Quantities such as charged and neutral particle dose rates in Si, coarse linear energy transfer (LET), charged-particle, and energy deposit spectra are provided at a cadence of up to one minute. Such data products are useful during intense solar particle events (SPEs).

High energy resolution. All quantities are also provided at high energy resolution at a cadence of one hour. These are the default data products during quiet times.

Neutron measurements. LND also measures the flux of thermal neutrons from beneath the lander and from above the lander. This provides limited information about differences in potential sub-surface water at the landing site and in the larger vicinity. Neutral-particle dose rate is also provided.

First measurements: During the first two lunar days (Jan 3 – 10 and Jan 31 – Feb 10, 2019) after landing on the Moon, LND measured an average dose equivalent of 1369 μSv/day [2] and the values reported in Tab. 1. For the same time period, the dose equivalent onboard the International Space Station (ISS) as measured with the DOSIS 3D DOSTEL instruments [3] was 731 μSv/day with contributions only from galactic cosmic rays (GCRs) of 523 μSv/day. The additional ~208 μSv/day is due to protons while crossing the South Atlantic Anomaly (SAA). Therefore, the daily GCR dose equivalent on the surface of the Moon is around a factor of 2.6 higher than the dose inside the ISS.

Dose rate [μGy/h]	Measured	Bkgnd	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

Table 1: Summary of dose rates measured on the lunar surface during solar activity minimum in early 2019.

Lunar albedo radiation: The Moon provides shielding from primary solar and galactic particle radiation but is also a source of secondary radiation which is created by the interaction of primary particles with lunar soils. LND has provided an additional measurement of albedo protons that now allows comparison with simulations of the spectrum of albedo protons, as shown in Fig. 3 (from [4]).

Solar Particle Events: LND observed its first SPE on May 6, 2019 registering proton energies up to 21 MeV. [5] provide combined proton energy spectra based on LND, SOHO/EPHIN, and ACE/EPAM measurements. That event occurred during solar activity minimum which the sun has now left. Since then, LND has registered many more such events, currently they occur at a rate of about one per month. [6] report the first ground level event (GLE) seen at Earth, the Moon, and Mars. A noteworthy example are the events on February 25 & 26, 2023 when LND measured a peak dose rate of >300 μGy/h from charged particles, i.e., about 30 times higher than the quiet-time background during solar activity minimum in early 2019 [2].

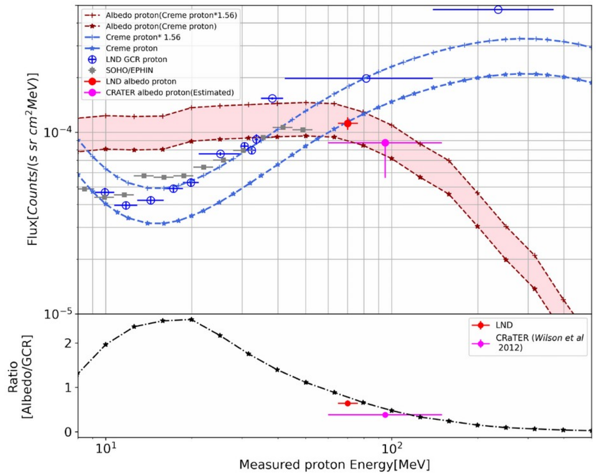

Figure 3: Top: GCR primary and albedo protons measured by LND (blue, red), SOHO/EPHIN (grey), and CRaTER (magenta). Bottom: Ratio. From [4].

Conclusions: After more than five years on the far side of the Moon, LND continues to measure dose rates from charged and neutral particles, and provides other critical dosimetric quantities such as LET spectra in preparation of human exploration of the Moon.

Acknowledgments: The work reported in this paper was supported by the Beijing Municipal Science and Technology Commission, grant no. Z181100002918003, and by NSFC grant no. 41941001. Developments and build of the LND instrument was supported by the German Space Agency, DLR, and its Space Administration under grant 50JR1604 to the Christian-Albrechts-University (CAU) Kiel.

References:

[1] Wimmer-Schweingruber, R.F., Yu, J., et al. (2020) *Space Science Reviews 216, 104.* https://doi.org/10.1007/s11214-020-00725-3.

[2] Zhang, S., Wimmer-Schweingurber, R.F., et al. (2020) *Science Advances*; *6: eaaz1334*, https://doi.org/10.1126/sciadv.aaz1334

[3] Berger, T. et al., (2017) *Journal of Space Weather and Space Climate 7, A08*, https://doi.org/10.1051/swsc/2017005

[4] Xu, Z., et al. (2022), *Frontiers in Astronomy and Space Sciences, vol. 9, id. 974946*, https://doi.org/10.3389/fspas.2022.974946

[5] Xu, Z. et al. (2019) *Astrophys. J. Lett., 902.2,L30*,https://doi.org/10.3847/2041-8213/abbccc

[6] Guo, J. et al., (2023) *Geophysical Research Letters*, *50.15,* https://doi.org/10.1029/2023GL103069