Million-year solar wind irradiation recorded in Chang'E-5 and Chang'E-6 samples

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Abstract

The long-term effects of Earth's magnetosphere on solar wind (SW) irradiation asymmetry between the lunar nearside and farside, and their implications for space weathering processes, remain poorly characterized. Here, we measure exposure ages and SW-induced amorphous rim thicknesses of individual grains from the Chang'E-5 (CE-5) and Chang'E-6 (CE-6) lunar soils to derive rim growth rates. Comparative analysis of SW irradiation records from CE-5, CE-6, and Apollo (11, 16, 17) samples reveals that CE-6 grains from the southern mid-latitude farside exhibit higher rim growth rates than those from the low-latitude nearside Apollo sites. This trend aligns with simulated lunar surface SW fluxes and is consistent with the hypothesis that reduced SW exposure on the nearside, due to Earth's magnetospheric shielding, may contribute to a persistent hemispheric asymmetry in SW irradiation. However, CE-5 samples from the northern mid-latitude nearside yield unexpectedly high rim growth rates, suggesting the potential involvement of additional local factors. The exact reasons for this anomaly remain unclear and warrant further investigation.

WHAT'S NEW?

- The growth rate of SW-damaged rims in Chang'e samples is significantly higher than in Apollo samples, with the CE-5 sample exhibiting an exceptionally high growth rate.
- The recorded exposure ages of the samples, along with the growth rate of SW-damaged rims, suggest a hemispheric asymmetry in the SW irradiation.

WHERE TO FIND?

The data: https://data.mendeley.com/datasets/xn73vjk95x/1

Paper: https://www.nature.com/articles/s41467-025-64239-8

BACKGROUND

Currently, eleven missions, including the two Chang'e, six Apollo, and three Luna missions, have collected and returned lunar samples. Both the Chang'e missions (CE-5 and CE-6) were conducted in this century. The CE-5 mission landed in the northeastern region of Oceanus Procellarum, collecting the youngest returned samples to date. The CE-6 mission landed in the Apollo crater, marking the first lunar far side sample collection. Due to the lack of atmospheric protection, the top layer of lunar soil is exposed to long-term solar wind irradiation. However, factors such as Earth's magnetosphere, the bow shock at the SW-magnetosphere interface, direct shielding by the Moon itself, and localized magnetic anomalies can lead to variations in the radiation environment across different regions of the Moon.

Materials and Methods

In total, four CE-5 shoveled samples (CE5C1000YJFM006, CE5C0400YJFM00505, CE5C0600YJFM00304, CE5C0300YJFM00401) and two CE-6 shoveled samples (CE6C0300YJFM001, CE6C0300YJFM00401) were used in this study. Through scanning electron microscope characterization, we selected 15 plagioclase grains (7 from CE-5 and 8 from CE-6) from these samples to prepare focused ion beam (FIB) cross-section. These grains all contain typical exposure features, such as micro-meteorite impact craters or melt splashes.

All the FIB cross-section were characterized using transmission electron microscopy (TEM), with the characterization area being the upper 1 μm of the section. The scanning transmission electron microscopy (STEM) and high-resolution transmission electron microscopy (HRTEM) images of the FIB cross-section indicate that the uppermost surface of the sample consists of a space weathering-induced amorphous rim, while the underlying matrix region contains solar particle tracks(Fig.1).

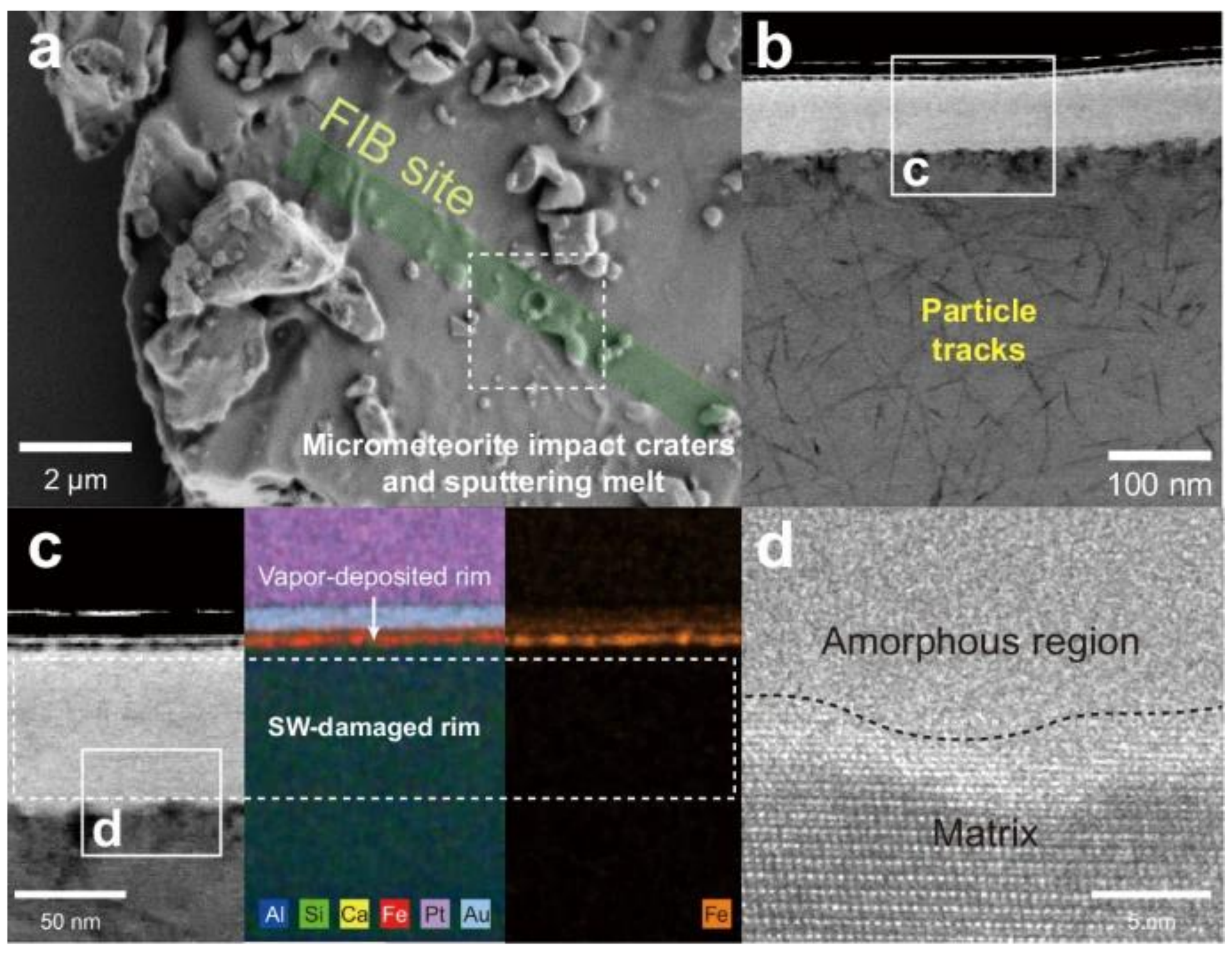

Fig. 1: The microscopic characteristics of representative studied grains.

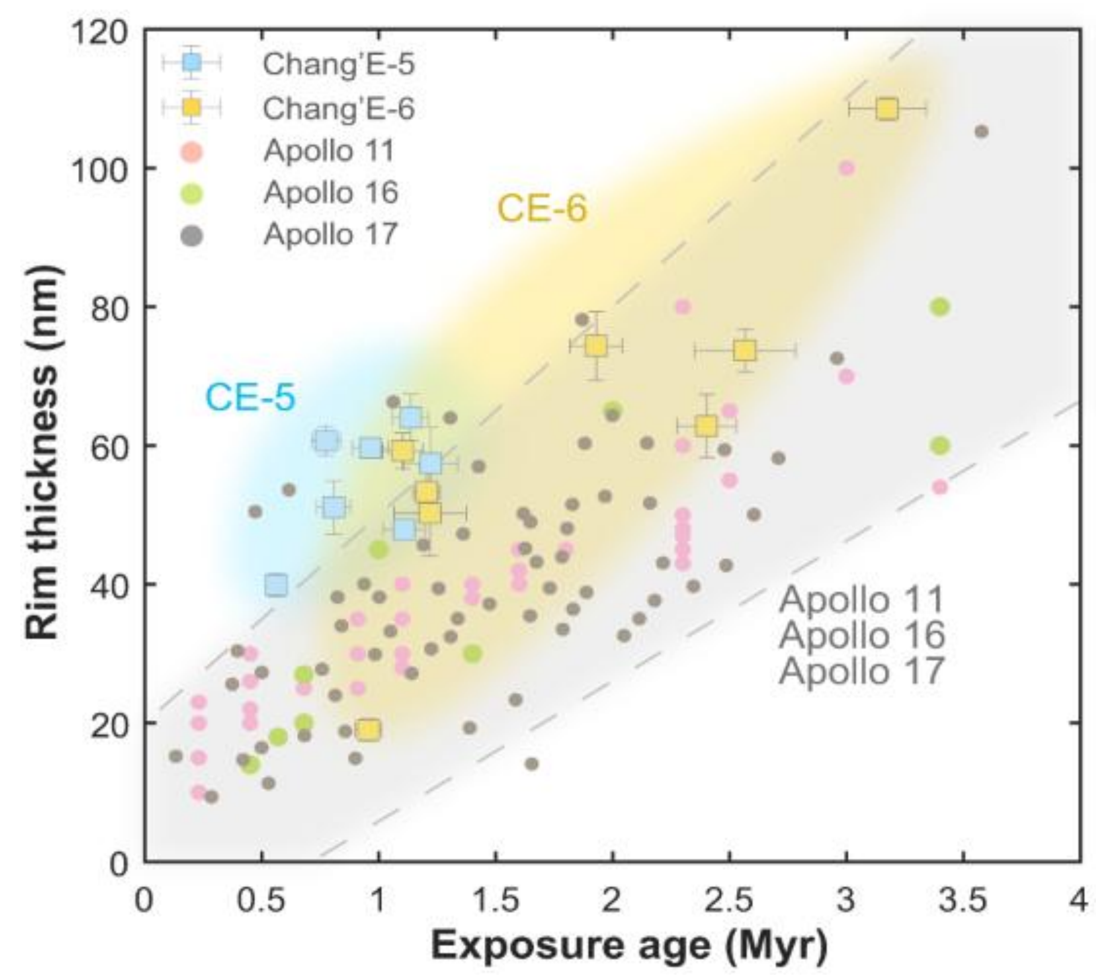

Fig. 2: Comparisons of SW-damaged rim thickness and exposure age in lunar grains from CE-5, CE-6, Apollo 11, 16, and 17 missions.

SW-damaged rims

In the CE-5 samples, their thickness ranged from approximately 40–64 nm, while in the CE-6 samples, their thickness varied from around 19 to 109 nm. Based on the growth rates calculated from solar particle tracks, CE-5 shows a rate of 55.96 ± 10.82 nm/Myr, while CE-6 shows a rate of 33.21 ± 6.16 nm/Myr. These rates are significantly higher than those of Apollo 11[1] (25.10 ± 1.76 nm/Myr), Apollo 16[1] (23.52 ± 5.36 nm/Myr), and Apollo 17[1] (25.40 ± 2.32 nm/Myr)(Fig.2).

Solar wind flux across sampling sites

Based on Xie et al. [2], we extracted the SW irradiation conditions (J_{avg} *and* $E_{f,avg}$) at the landing sites of Chang'e missions and Apollo 11, 16, and 17. Considering the differences in latitude, we corrected using the factor cos ϑ, with ϑ defined as the sampling site's latitude. The (J_{avg_cor}, E_{f,avg_cor}) values for CE-5 and CE-6 are (0.2640, 0.2443) and (0.3157, 0.3090). For Apollo 11, 16, and 17, these values are (0.2321,0.2036), (0.2198,0.1130) and (0.2379, 0.2089)(Fig.3).

Influence of solar wind irradiation on SW-damaged rim growth rates

Based on the measured SW-damaged rim growth rates (k) and the simulations, we constructed correlation plots between average SW fluxes and rim growth rate k across these sampling sites(Fig.3). Excluding the CE-5 site, the remaining four sites appear to exhibit a positive correlation between k and both J_{avg} *and* $E_{f,avg}$ *with* Pearson's correlation coefficients of 0.7758 and 0.7260 (n=4), respectively. However, the corresponding P-values (0.2242 and 0.2740) indicate the correlations do not reach statistical significance at the conventional threshold ($p<0.05$). This is primarily attributed to two factors: limited sample size due to the small number of sampling sites, and high data-point clustering caused by the geographic proximity of Apollo sampling sites, which leads to similar rim growth rates. Notably, the CE-6 sample from the mid-latitude lunar farside exhibits a relatively higher k than the low-latitude nearside Apollo samples. This trend aligns with the hypothesis that shielding by Earth's magnetosphere reduces SW exposure on the lunar nearside, potentially giving rise to a persistent hemispheric asymmetry in SW irradiation. Nonetheless, this interpretation remains provisional, as alternative environmental and structural factors—such as surface temperature variations (which may affect annealing efficiency), as well as local topography and regolith porosity (which may modulate SW irradiation or implantation conditions)—may also contribute to the growth rate of SW-damaged amorphous rims and cannot be definitively ruled out.

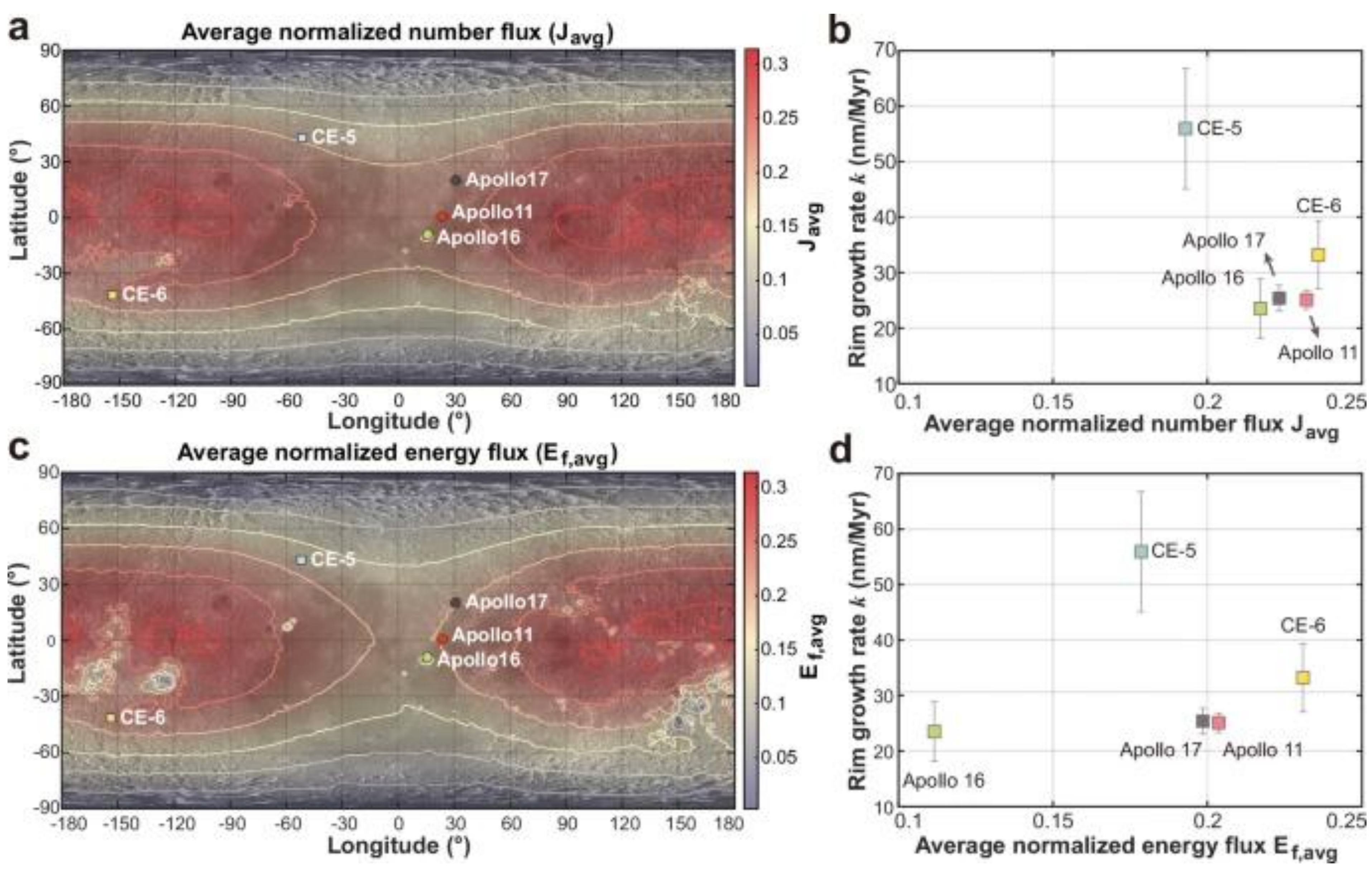

Fig. 3: Maps of the lunar surface showing average normalized SW number flux (J_{avg}) and energy flux ($E_{f,avg}$), alongside profiles of SW-damaged rim growth rate (k) versus J_{avg} and $E_{f,avg}$.

References

1. Keller, L. P., Berger, E. L., Zhang, S. & Christoffersen, R. Solar energetic particle tracks in lunar samples: a transmission electron microscope calibration and implications for lunar space weathering. Meteorit. Planet. Sci. 56, 1685–1707 (2021).
2. Xie, L. et al. Global Hall MHD simulations of the solar wind implantation flux on the lunar surface. Planet. Sci. J. 4, 218 (2023).

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