SOLAR-ENERGETIC-PARTICLE TRACK-PRODUCTION RATES IN INTERPLANETARY DUST GRAINS AT 1 AU.

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Introduction: Heavy (Z>26) solar energetic particles (SEPs) with energies ~1 MeV/nucleon are known to leave visible damage tracks in meteoritic materials. The density of such 'solar flare tracks' in lunar and asteroidal samples has been used as a measure of a sample's exposure time to space, yielding critical information on planetary space weathering rates [e.g., 1] and the dynamics and lifetimes of interplanetary dust grains [e.g., 2, 3]. Knowledge of the SEP track accumulation rate in planetary materials at 1 au is critical for properly interpreting observed track densities. Here, we report comparisons of the SEP track-accumulation rate at 1 au from two separate sources: (i) laboratory analysis of returned Apollo sample 64455 [1] and (ii) in-situ measurements of the Z>26, ~1 MeV/nuc SEP flux at the L1 Lagrange point by the *Advanced Composition Explorer* (ACE) spacecraft [4]. Full details are available in Poppe et al. (2023) [5].

Apollo Sample 64455: Lunar sample 64455 is an oriented, glass-coated impact-melt rock returned by the Apollo 16 astronauts from the environs of the South Ray crater. Multiple studies have established the surface exposure age of 64455 to be 2 Myr based on cosmogenic nuclide abundances [e.g., 6, 7] and such age is consistent with other South Ray crater samples. Keller et al. (2021) [1] used scanning transmission electron microscope imaging of 64455 thin slices to count the SEP-induced damage track density, i.e., see Figure 1. Using the observed track density and the constrained surface-exposure age, [1] derived an SEP track accumulation rate at 1 au of 8x10^3 tracks cm^{-2} s^{-1} str^{-1}. The rate is significantly lower than that reported in earlier studies of track densities in 64455 by [1] and is attributed to improved measurement techniques (i.e., TEM imaging versus chemical etching).

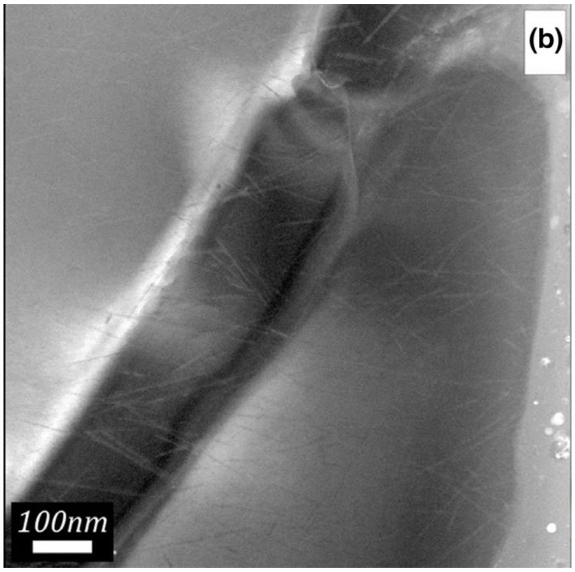

Figure 1: *Dark-field STEM image of a FIB section of Apollo sample 64455 showing SEP tracks as narrow linear features throughout [1].*

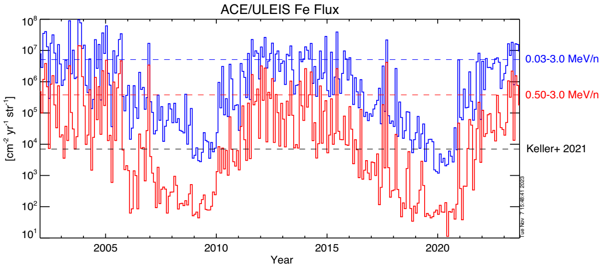

Figure 2: *The monthly averaged SEP flux measured by ACE/ULEIS at L1 over two solar cycles in two energy ranges [5]. Mean SEP fluxes are shown as horizontal dashed lines.*

ACE SEP Measurements: We use in-situ particle observations of the 0.50–3.0 MeV/nuc Fe-group SEP flux taken by NASA's *Advanced Composition Explorer* (ACE) to calculate a flux of track-inducing particles at 1 au. Since 1998, the Ultra-Low-Energy Isotope Spectrometer (ULEIS) instrument onboard ACE has been continuously measuring the flux of 0.03–3.0 MeV/nuc particles from Z=4 (He) to Z=28 (Ni) [8]. Figure 2 shows the Z=26 (Fe)-group SEP flux as a function of time from 2002 to 2023 for two energy ranges: (blue) the full 0.03–3.0 MeV/nuc energy range measured by ULEIS and (red) the narrower 0.5–3.0 MeV/nuc energy range in which SEPs are known to generate damage tracks in meteoritic materials. In this restricted energy range, *ACE*/ULEIS observes an SEP flux of 6.0x10^5 cm^{-2} yr^{-1} str^{-1} (red dashed line in Figure 2).

Comparison of SEP Fluxes & Discussion: In Figure 2, we also plot the SEP track-accumulation rate reported in [1] as the black dashed line, which is a factor of ~25x *less* than that observed by *ACE*/ULEIS. To further confirm this difference, we also verified the *ACE*/ULEIS rate via analysis of *Wind*/STEP measurements [9] and found an identical rate. Here, we consider several hypotheses for the nature of this discrepancy.

Track Registration Efficiency: The energy range over which we integrated *ACE*/ULEIS Fe-group fluxes (0.5–3.0 MeV/nuc) is taken from previous work investigating the sensitivity of meteoritic materials to SEP damage-track accumulation [e.g., 10]. We investigated whether a reduced sensitivity could account for the high rate of ACE-measured track accumulation; however, we could only achieve agreement by fine-tuning the sensitive energy range to an implausibly narrow range that conflicts with previous laboratory measurements.

Thermal Annealing of Tracks: Temperatures >~400°C can induce thermal annealing of SEP-induced damage tracks [e.g., 11]; however, such temperatures are far higher than those routinely encountered on the lunar surface. Furthermore, no evidence of 'gapped' tracks are present in the study of 64455 [1] that would otherwise indicate active annealing.

Grain Surface Erosion: Exposure to keV-energy solar wind ions will sputter atoms from the uppermost monolayers of 64455 and over time, act to reduce the apparent track density. Using typical values of solar wind flux at 1 au and standard sputtering yields, we find that 64455 should have experienced ~14 µm of erosion. We employed a simple Monte Carlo routine to model the simultaneous generation and erosion of tracks in an exposed lunar sample and found that the equilibrium track density was reduced by a factor of ~2; however, this does not account for the factor of ~25 difference between *ACE* and 64455 TEM measurements.

SEP Shielding at the Moon: While the *ACE* measurements are technically not at the immediate lunar surface, we find no reason to account for a factor of 25x difference in the SEP flux at the Moon. The Moon does spend ~25% of its time crossing the terrestrial magnetotail; however, this plainly cannot account for the factor of 25x difference and furthermore, recent work has shown that the magnetotail does not shield the lunar surface from SEPs [12]. Crustal magnetic fields on the lunar surface are thought to deflect and shield ~1 keV solar wind protons from reaching the surface, but are not believed capable of shielding heavy, MeV/nuc-energy particles.

Long-term SEP Variability: The SEP flux measured by *ACE* is technically only a measure of the past two solar cycles over ~22 years, while 64455 has a space exposure age of ~2 Myr. Nevertheless, the available history of solar activity over the past hundreds [e.g., 13] and thousands to tens-of-thousands of years [e.g., 14] does not indicate that the most recent 22 years have an anomalously high SEP flux compared to ~Myr baselines.

Conclusions: At present, we conclude that there is a fundamental gap somewhere in our understanding of the formation of SEP-induced damage tracks in meteoritic materials. On one hand, the well-established age and observed track density present in 64455 provides a strong data point for a relatively low track formation rate of $8x10^3$ tracks cm^{-2} s^{-1} str^{-1} [1]. On the other hand, in-situ measurements by the *ACE*/ULEIS instrument confirmed by concurrent measurements by *Wind*/STEP provide a much higher track formation rate of $6.0x10^5$ cm^{-2} yr^{-1} str^{-1} [5]. To address this knowledge gap, we urge further laboratory measurements of SEP track formation in a variety of relevant mineral phases across relevant energies as well as in-situ measurements on the lunar surface of the $Z>26$, 0.5–3.0 MeV/nuc SEP flux. Additionally, analysis of other suitably age-dated samples either in the current Apollo sample collection or in new samples to be returned by the *Artemis* astronauts would help to further confirm the results determined from lunar sample 64455.

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