DISCOVERY OF A LUNAR COLD SPOT AT THE APOLLO 16 SOUTH RAY CRATER.

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Introduction: Temperature mapping of the Moon by the Diviner instrument on the Lunar Reconnaissance Orbiter [1] has revealed regions of anomalously low nighttime temperature surrounding fresh impact craters [2]. These enigmatic features, termed cold spots, are ray-like in appearance and typically extend ~10-100 crater radii, suggesting that impact craters can modify planetary surfaces to significantly greater distances than was previously realized. Cold spots are among the youngest known population of craters with a global size-frequency distribution consistent with a population age of ~150 ka and the largest cold spots, dated by the accumulation of craters on their continuous ejecta, fading on timescales of ~1 Ma [3]. Bandfield et al. (2014) [2] proposed that cold spots could be explained by the decompaction of the upper several centimeters of regolith, resulting in a lower thermal inertia layer.

Using improved Diviner nighttime temperature maps [4], we identify a cold spot around South Ray crater (figure 1A), a ~700-m recently formed rayed crater at the Apollo 16 landing site [5,6]. While faint compared to other similarly sized cold spots (figure 1B), South Ray crater exhibits a distinct, ray-like -1 K temperature anomaly extending to ~30 crater radii. In this work, we: 1) compare the thermophysical properties of South Ray crater's cold to other cold spots; and 2) re-evaluate Apollo 16 relative density results to understand the properties and formation of cold spots.

Cold spot fading: We propose that South Ray cold spot's comparatively smaller size and faint temperature anomaly can be explained by fading. South Ray crater has an estimated age of ~2 Ma determined from the cosmic ray exposure ages of Apollo 16 samples [7,8]. Williams et al. (2018) [3] used crater counts to date several similarly sized cold spot craters and found the oldest to be ~1.3 Ma, similar to, but slightly younger than, the estimated age of South Ray crater. Figure 2 shows the trend in temperature anomaly with age for these cold spots. South Ray cold spot falls cleanly along a power-law fit to the Williams et al. (2018) [3] cold spots, indicating that South Ray crater's age is consistent with being slightly older but also more faded than the other cold spots. This would indicate that South Ray crater is the oldest known cold spot crater.

Regolith properties from astronaut footprints and thermal modeling: South Ray crater's cold spot extends to the location of the Apollo 16 Lunar Module (LM) and Extravehicular Activity (EVA) traverses. Therefore, some of the Apollo 16 regolith samples and in-situ experiments are representative of cold spot material. During the Apollo missions, the depths of 776 astronaut footprints were used to estimate the relative density of the upper ~15 cm of regolith [9,10], where relative densities of 0% and 100% correspond to the minimum and maximum achievable packing densities of regolith, respectively. Figure 3 shows the mean relative density for intercrater areas at each of the Apollo sites reported in Mitchell et al. (1974) [10]. The mean relative density at Apollo 16 is ~6 percentage points lower than the other sites. A two-sample z-test comparing the Apollo 16 mean relative density to the other Apollo sites yields a p-value $\ll 0.05$, confirming that the Apollo 16 mean relative density is statistically different from the other Apollo sites.

Regolith properties can also be determined using nighttime temperature measurements. Figure 1C shows the cooling behavior for South Ray cold spot, which we fit using a 1D thermal model [11] where density ρ increases as a function of depth z: $\rho = \rho_d - (\rho_d - \rho_s)e^{-z/H}$, where ρ_s and ρ_d are the density at the surface and depth respectively, and H is an exponential scale height. Figure 1D shows the density profile which best fits the nighttime temperature data for South Ray cold spot and the background regolith outside of the cold spot. We integrate the best-fit density profiles over the upper 15 cm and convert to an equivalent relative density (assuming ρ_{min}=1100 kg/m^3 and ρ_{max}=1800 kg/m^3): 59% for South Ray cold spot and 75% for background regolith. Using this method, we estimate South Ray cold spot has a relative density ~16 percentage points lower than background regolith, a greater difference than was observed using astronaut footprints. This discrepancy may be caused by uncertainties in measurements, thermal modeling, or the conversion of footprint depths to relative density. However, both methods see a roughly similar decrease in relative density for South Ray cold spot. These results show that ground-truth observations support the cold spot mechanism proposed by Bandfield et al. (2014) [2] where a decompaction of the upper centimeters of regolith results in lower thermal inertia. This is also relevant for future landed missions, as it demonstrates that meaningful differences in regolith properties can be measured using regolith compaction from astronaut footprints and likely from rover wheel tracks.

References: [1] Paige et al. (2010) *Space Sci. Rev., 150,* 125-160. [2] Bandfield et al. (2014) *Icarus, 231*, 221-231. [3] Williams et al. (2018) *JGRP, 123,* 2380-

2392. [4] Powell et al. (2022, submitted) *JGRP.* [5] Hodges et al. (1973) *LPSC, 4.* [6] Ulrich et al. (1975) *LPSC, 6,* 832. [7] Drozd et al. (1974) *Geo. Cosmo. Act., 38,* 1625-1642. [8] Arvidson et al. (1975) *The Moon, 13,* 259-276. [9] Mitchell et al. (1972) *Apollo 16 Prelim. Sci. Rept.* [10] Mitchell et al. (1974) *Apollo soil mechanics experiment S-200.* [11] Hayne et al. (2017) *JGRP, 122,* 2371-2400.

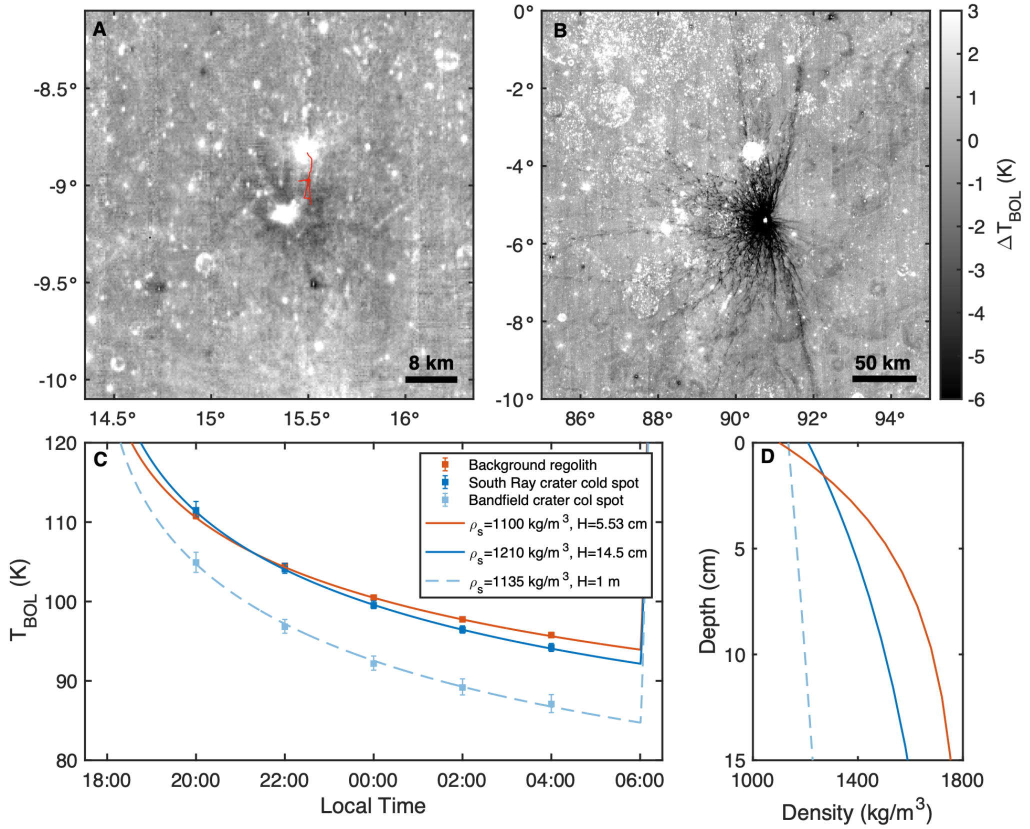

Figure 1. A) Diviner bolometric temperature anomaly for South Ray crater's cold spot at 04:00 local time. The red lines show the Apollo 16 LM and EVA traverse paths. B) Bolometric temperature anomaly for Bandfield crater's cold spot. C) Nighttime temperature for both cold spots and typical regolith fit using a thermal model [11]. D) Density profile of thermal model fits.

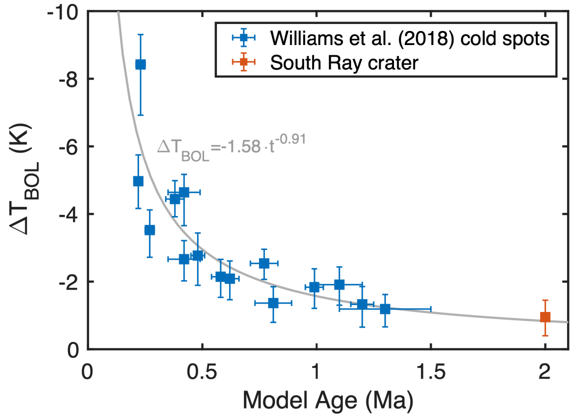

Figure 2. Peak bolometric temperature anomaly at midnight versus age for large (>800 m) cold spot craters dated by Williams et al. (2018) [3] and South Ray crater (~700 m) [7,8]. For each cold spot, temperature was binned radially in 3 crater radii annuli.

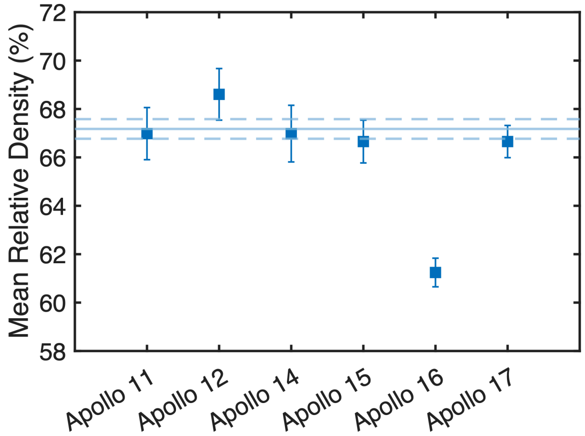

Figure 3. Mean relative density of the upper ~15 cm of regolith at each Apollo site derived from the depth of astronaut footprints [10]. Error bars show 1 standard error. The horizontal lines show the mean and standard error for all sites excluding Apollo 16.