EXAMINATION OF LUNAR SUBSURFACE CAVITIES USING THERMAL INERTIA AND TEMPERATURE MAXIMUM TO MINIMUM RATIOS

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Introduction: Previous studies have revealed a small number of subsurface cavities, including lava tubes, lava flow pits, and impact melt pits on the Moon [1-4]. The interiors of such cavities are theorized to have been protected from micrometeorite bombardment, solar radiation, space weathering, and extreme diurnal temperature swings over long periods of lunar geologic time. As a result, these subsurface features can provide access to pristine crustal samples and stratigraphy. These cavities could also provide protection of important *in-situ* volatiles, such as water ice, that would enable future exploration missions by supporting otherwise operational constraints, including the supply of propellants and life support. In addition, subsurface cavities could serve as the sites of protective habitats for future lunar explorers.

The goal of this research is to establish a methodology using thermal inertia and maximum to minimum temperature ratios to detect and characterize lava tubes and other subsurface cavities in the lunar subsurface. Using data from the Lunar Reconnaissance Orbiter (LRO), thermal inertia and maximum to minimum temperature ratio maps were created and analyzed. Five locations were analyzed and four of those show evidence of a subsurface cavity being present.

Background: Thermal inertia (P) describes the resistance of a material to changes in temperature [5]. It is defined as:

$$P = \sqrt{K\rho c} \quad (1),$$

where K is thermal conductivity, ρ is density, and c is specific heat. Unfortunately, these parameters cannot be directly measured using remote sensing techniques, so thermal inertia is typically estimated from other directly-measured data or it is modeled. One way to approximate thermal inertia is by calculating apparent thermal inertia (ATI), which is defined as [5]:

$$ATI = \frac{1-a}{\Delta T} \quad (2),$$

where a is albedo and ΔT is the difference in temperature over a diurnal cycle. In order to calculate the most accurate ΔT value, T_{max} and T_{min} (maximum and minimum temperatures, respectively) need to be calculated using [5]:

$$T_{max} = T_1 + \frac{(T_1-T_2)[\cos(\omega t_{max}) - \cos(\omega t_1)]}{\cos(\omega t_1) - \cos(\omega t_2)} \quad (3)$$

$$T_{min} = T_2 + \frac{(T_1-T_2)[\cos(\omega t_{min}) - \cos(\omega t_2)]}{\cos(\omega t_1) - \cos(\omega t_2)} \quad (4),$$

where t_{min} and t_{max} are time minimum and maximum respectfully; t_1 and t_2 are day and night time respectfully; T_1 and T_2 are day and night temperature respectfullyand ω is rotational angular frequency. A more sophisticated treatment allows the determination of thermal inertia from ATI [6]:

$$P = ATI\left(\frac{S_0 C_t}{\sqrt{\omega}}\right)\left\{\frac{A_1[\cos(\omega t_2-\delta_1)-\cos(\omega t_1-\delta_1)]}{\sqrt{1+\frac{1}{b}+\frac{1}{2b^2}}} + \frac{A_2[\cos(\omega t_2-\delta_2)-\cos(\omega t_1-\delta_2)]}{\sqrt{2+\frac{\sqrt{2}}{b}+\frac{1}{2b^2}}}\right\} \quad (5),$$

where S_0 is the solar constant (1,366 W/m^2 at 1 AU) C_t is the atmospheric transmittance (1 for the Moon), δ_1 is solar declination at time t_1, δ_2 is solar declination at time t_2, A_1 and A_2 are Fourier coefficients, and b is a parameter dependent on the local time when the maximum daytime temperature is reached:

$$b = \frac{\tan(\omega t_{max})}{1-\tan(\omega t_{max})} \quad (6).$$

The ground surface above the roof of a subsurface cavity should appear to have lower thermal inertia, and higher T_{max} to T_{min} ratio, than the surrounding surface. The roof of a cavity would get warmer in a shorter amount of time during the day than the surrounding area because the roof has less volume, and therefore smaller thermal mass, than the surrounding area. Conversely, the roof of a cavity would get cooler in a shorter amount of time at night than the surrounding area because it has a smaller thermal mass.

Methods: To locate subsurface cavities, DIVINER data was used to calculate ΔT, ATI, and P maps [5] of the Moon for a complete diurnal cycle. The available temperature maps for day and night were adjusted for local time and Julian date to calculate the T_{max} and T_{min} maps using Equations 3 and 4. Those maps were used to calculate ΔT and the maximum to minimum temperature ratio maps. In combination with a terrain slope corrected DIVINER albedo map, we then calculated ATI and P using Equations 2 and 5, respectively. The data processing was done using ENVI and MATLAB software.

Results and Discussion: Five areas of suspected subsurface cavities were investigated (Fig. 1): Mare Tranquilities, “Highland 1”, “Highland 2”, Rima Sharp, and Lacus Mortis. These areas were selected based on available data coverage and are places where skylights have previously been reported [1-4].

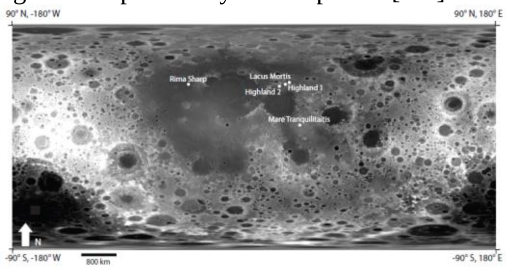

Figure 1: LOLA DEM showing locations of the five sites of interest (white circles).

Mare Tranquilitatis: The Mare Tranquilitatis skylight has larger thermal inertia than the surrounding area, which is what is expected for the signature caused by a skylight. Similarly, the Mare Tranquilitatis skylight has a smaller T_{max} to T_{min} ratio than the surrounding area which is also consistent with the presence of a subsurface cavity. However neither the thermal inertia signature nor the T_{max} to T_{min} ratio signature are linear, suggesting that the cavity may not be a lava tube. Instead, the cavity may be some sort of isolated, near-circular chamber, and the skylight may actually be a pit.

Highland 1: The Highland 1 skylight has a large thermal inertia signature and small T_{max} to T_{min} ratio signature, which is consistent with the expected thermal signature of a skylight. A north-south trending thermal anomaly just west of the skylight has a lower thermal inertia (Fig. 2) and a higher T_{max} to T_{min} ratio (Fig. 3) than the surrounding area. This thermal anomaly is curvilinear in shape, and connects with the skylight. A second thermal anomaly trends northeast-southwest, but does not connect with the skylight,. This anomaly is also linear and has a lower thermal inertia and higher T_{max} to T_{min} ratio than the surrounding area. These anomalies could represent lava tubes.

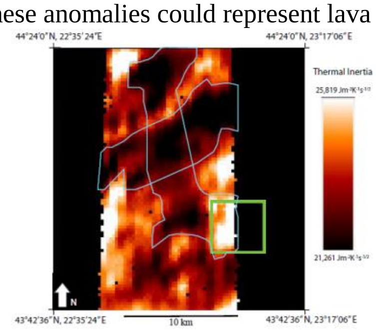

Figure 2: Thermal inertia map of Highland 1. Brighter colors denote larger thermal inertia values. Darker colors denote smaller thermal inertia values. Black indicates areas of missing data or very low thermal inertia values. The green box outlines where the skylight is located. The blue polygons outline the suspected lava tubes.

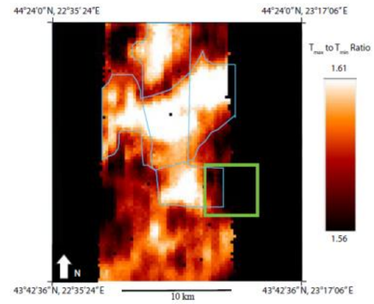

Figure 3: T_{max} to T_{min} ratio map of Highland 1. Brighter colors denote larger ratio values. Darker colors are smaller ratio values. Black indicates areas of missing data or very low ratio values. The green box outlines where the skylight is located. The blue polygons outline the suspected lava tubes.

Highland 2: A linear feature to the northwest of the skylight located here has a lower thermal inertia than the surrounding area. It also has a higher T_{max} to T_{min} ratio than the surrounding area. We believe this feature is associated with a lava tube in the subsurface. However, the thermal anomaly does not appear to connect to the known skylight. If a lava tube is present, it may turn southward to connect to the skylight, but a gap in DIVINER data coverage around the skylight precludes testing this hypothesis.

Rima Sharp: Both the thermal inertia and the T_{max} to T_{min} ratio techniques failed to highlight any anomalies consistent with the surface expression of a lava tube or any other subsurface cavity at Rima Sharp. Although there are several possible reasons for this, we believe most likely reason is that the lava tube is too deep to be detected using thermal methods.

Lacus Mortis: Although a thermal anomaly is difficult to see in the thermal inertia map, one is apparent in the T_{max} to T_{min} ratio map, showing higher ratio values compared to the surrounding area. In addition, the thermal anomaly is linear in shape, and connects perfectly to the skylight. Based on this, we believe a lava tube may be present in the subsurface.

Conclusions: Using both the thermal inertia and T_{max} *to* T_{min} ratio techniques, four of the five sites of interest have thermal signatures consistent with the presence of a subsurface cavitiy. Although it was previously suspected that lava tubes may be present at Highland 1, Highland 2, and Lacus Mortis [1,4], it has not been explored until now. This methodology could be applied to other sites on the Moon.

References: [1] Ashley, J.W., et al. (2011) *LPSC XLII*, abs.2771. [2] Meyer, J.A. (2012) UTEP M.S. Thesis. [3] Chappaz, L., et al. (2014) *LPSC XLV*, abs. 2019. [4] Wagner, R.V. and Robinson, M.S. (2014) *Icarus*, 237, 52-60. [5] Scheidt, S., et al. (2010) *JGR*, vol. 115, F02019. [6] Xue, Y. and Cracknell, A.P. (1995) *IJRS*, vol. 3, (431- 446).