Thermal Environment of Lunar Pits and Caves: Implication for Future Lunar Missions and Volatiles. T. Horvath[1], A. X. Wilcoski[2,3], P. O. Hayne[2,3], and D. A. Paige[1], [1]Department of Earth, Planetary, And Space Sciences, University of California, Los Angeles (tylerhorvath@ucla.edu), [2]University of Colorado, Boulder, [3]Laboratory for Atmospheric and Space Physics, Boulder, Colorado.

Introduction: The discovery of lunar pits [1] with subsurface overhangs brought forth a wave of mission concepts to explore and potentially inhabit the lava tubes in which they may lead. A primary point of consideration for such missions is the lunar thermal environment, which varies from 100-400 K on typical equatorial surfaces over the course of the day. The cold night has proven to be the limiting factor for the longevity of nearly all lunar missions, past and present. While the thermal environment of lunar caves had been hypothesized to be more stable and favorable than that of the lunar surface, in-depth analysis had yet to be performed. We sought to understand the thermal environment of lunar pits and the caves they may host by analyzing remote radiometric observations from the Diviner Lunar Radiometer Experiment aboard the Lunar Reconnaissance Orbiter (LRO) and by creating computational thermal models.

Thermal Environment: Initially we began the work of characterizing the thermal environment of lunar pits and caves in support of the proposed discovery class mission Moon Diver as it would play a pivotal role in the thermal design of the Axel rover [2]. However, after promising initial results, we expanded on the study in hopes of understanding the thermal environment more intimately.

Our recently published results [3] showed that lunar lava tubes with skylights behave as near-perfect blackbody cavities, a hypothetical structure that is a perfect absorber and emitter of radiation, exhibiting a temperature of ~290 K at 1 AU distance from the Sun. Far from the skylight temperatures vary minimally (< 1 K) throughout the lunar day (Fig 1.). In fact, everywhere within the pit-cave system experiences higher nighttime temperatures and lower diurnal amplitude. This is due to the highly insulating nature of the lunar regolith, and is supported through thermal measurements from Diviner and computational models. This behavior appears to hold for caves of even minor length, and helps make lunar pits strong candidate sites for future human exploration and habitation.

Volatile Stability: Our thermal and ice stability models have shown that pits and caves situated near the poles are likely to be too warm to cold trap water ice (Fig. 2), attributed to the blackbody nature of these features. Only if they are doubly shadowed, locations only illuminated by multiply scattered photons within permanently shadowed regions (PSRs), would ice remain

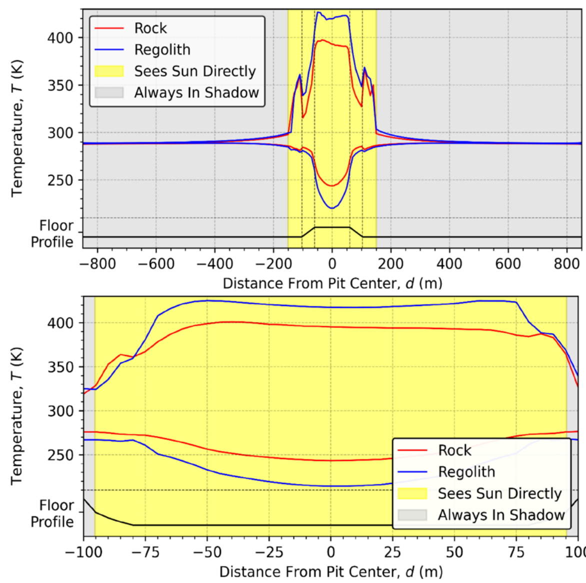

Figure 1: Maximum and minimum floor temperatures of potential caves stemming from the Tranquillitatis pit (100 m diameter). The temperature of permanently shadowed regions within the caves converge quickly to ~290 K, just shy of a the 295 K expected of a perfect blackbody cavity at this location.

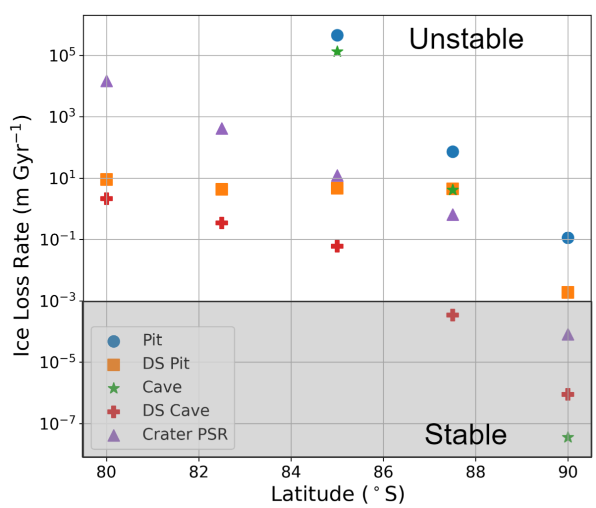

Figure 2: Water ice stability of pits with, and without caves situated near the lunar south pole. Pit and Cave refer to a pit without a cave and a pit with a cave located outside of a PSR, respectively. DS is doubly shadowed, or features located within PSRs.

stable. Water ice stability in this context refers to ~1 mm/Gyr of ice loss [4]. Given the low probability of pits and caves existing within a doubly shadowed region, these locations are not likely to be significant reservoirs of water ice on the Moon, though a cave could potentially store more water than the surface alone.

Mission Implications: The harsh lunar thermal environment has limited the length of most surface missions to the daytime, as the ~15 days of frigid night are difficult to survive. Surviving such conditions would require either massive batteries and/or a radioisotope thermoelectric generator (RTG) to power survival heaters for an extended amount of time. Placing assets in lunar caves, such as what may be present at the Mare Tranquillitatis, Mare Ingenii, or Marius Hills pits, may require minimal to no survival heating as their temperatures remain a steady ~290 K throughout the night. There are also the additional benefits of protection from cosmic radiation and micrometeorites, and > 3 billion years of proven structural stability.

While enticing, these locations come with the significant challenge of traversal, with vertical walls bounding all sides of the Mare Tranquillitatis and Marius hills pits, and steep slopes leading into the Mare Ingenii pit [5]. Moon Diver hoped to overcome this challenge by rappelling into the Tranquillitatis pit [2], while others have explored the possibility of directly landing within [6] or even hopping into the feature [7]. It must also be noted that thermal stability can be achieved without the need to enter a cave, covering a habitat in ~20 cm of regolith would provide the same insulative effect, though this would require the ability to move a large volume of soil.

For human exploration, this provides an exciting possibility of using caves as a location for establishing a sustained presence on the Moon. If built within the thermally stable reaches of a cave, free from the hazards the lunar environment presents, it drastically decreases the engineering requirements of a habitat. It also introduces the possibility of astronauts exploring and moving about the cave without the need for a large EVA suit as the cave's temperatures are already regulated, an airtight pressure suit with other life support capabilities may be all that is needed. This would drastically improve the maneuverability of the astronauts as they expand their habitat and perform in-situ experiments within the cave, providing a unique possibility of rapid habitat expansion and better science.

Conclusion: Taking advantage of the favorable environment and structure of a natural lunar cave brings a promising set of benefits that must be considered in this new age of human space exploration. The freedom from having to account for the multitude of hazards that exist on the lunar surface may improve the prospect of long term habitation of the Moon. However, the issue of entering and exiting such features must be carefully studied and new technologies must be developed as we currently do not have this capability. If these targets are to be considered for future missions the work must be done now to find a solution. There is also a very low probability that water ice exists within lunar pits and caves, and should therefore be considered primarily for the exploratory benefits and non-volatile scientific possibilities.

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