ASTROBOTIC TECHNOLOGY: PLANETARY PITS AND CAVES FOR SCIENCE AND EXPLORATION.

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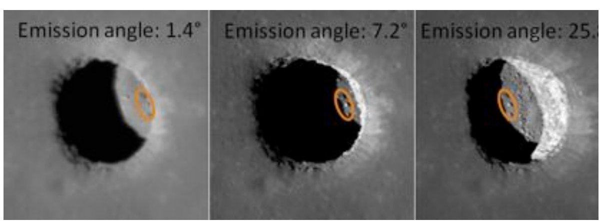
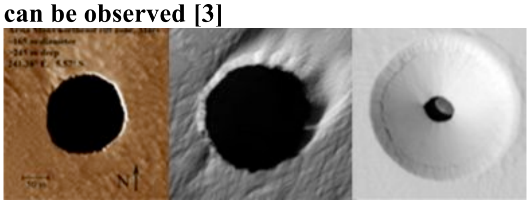
Introduction: This paper describes lunar pits and caves as a potential destination for future science and exploration missions and crewed lunar outposts.

Pit and Cave Science: Pits and caves on bodies throughout the solar system are opportunistic targets to study planetary origins, geology, climate, and potentially even biology. Pit crater chains have been identified on Venus [1]; Earth [2] the Moon [3][4]; Mars [5] [6]; Eros [7]; and Europa [8].

Caves, pits, and lava tubes present unique opportunities to investigate planetary volatiles, mineralogy, origins, morphology, geologic history, and exposed surfaces without regolith cover. Because high-latitude environments are cryogenic and tube walls are regolith-free, volatiles accrete on clean cave walls and floors. As tubes cool for weeks, secondary minerals appear on the surfaces, entrapping pristine evidence of formation processes. Pit descent enables access to tens of meters of geologic column otherwise impossible to view. Thermal imaging reveals temperature transience of regolith and bedrock as solar illumination transits on pit walls. Despite the discovery of planetary pits and caves, they were not identified or adopted as a subject of study in the most recent decadal survey.



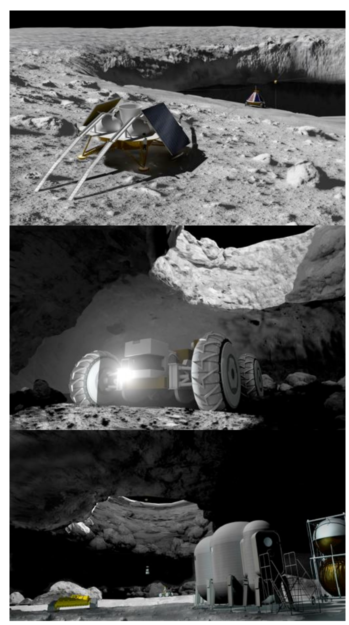
Three views of the Mare Tranquillitatis skylight on the Moon. Void space under an overhanging ceiling can be observed [3]



Possible skylights on Mars [5]

Pit and Cave Exploration: In addition to their rich scientific potential, planetary pits and caves could benefit future human exploration missions. Planetary caves could provide a safe haven from a number of hazardous conditions that are inherent to planetary environments. For instance, human habitats in lunar caves would protect crews from the extreme temperature variations, radiation bombardments, and micrometeorite hazards inherent in living and working on the lunar surface. By utilizing in situ cave conditions to protect human habitats, the cost of human exploration of destinations like the Moon and Mars could be significantly lowered through mass savings and reduced mission complexity. Although the utilization of caves for human exploration could yield great benefits, the potential for risk to human explorers demands robotic precursors as the first step to cave exploration and scientific study.

Robotic explorers can approach, enter, and model these features at thousand-fold increased resolution relative to orbital means, and perform physical sampling and analysis to achieve unique science not otherwise possible. Skylights, formed by partial cave ceiling collapse, provide access to subsurface voids. While robotic exploration of skylights and caves can seek out life, investigate geology and origins, and open the subsurface of other worlds to humankind, it is a daunting venture. Planetary voids present perilous terrain that requires innovative technologies for access, exploration, and modeling. The robots that venture into caves must leap, fly, or rappel into voids, traverse rubble and high grade slopes, navigate safely in the dark, self-power, and explore auton-



Robotic flyover, apron viewing, floor-traverse and caving enable a new class of missions for scientific exploration of subsurface features

omously with little or no communication to Earth. Exploiting these features necessitates a leap in technology from current planetary missions, which land with large error ellipses in statistically safe terrain, rove slowly and cautiously across the surface, depend on the Sun for power and light, and rely heavily on human commands.

Missions: Planetary pit and cave exploration demands bold new technology for flyover, apron viewing, pit descent, rock crawling, and robotic caving [9]. Modeling, visualizing, and compressing the multi-physical data associated with scientific investigation of this kind will require new techniques and data representation that must be prototyped and integrated with science, and evaluated in analog experimentation. Some pits are amenable to drive-in via trafficable ramps. A mission to pits and caves would conceive, plan, and evaluate mission concepts in a collaborative, interdisciplinary manner that draws from the needs of science interrogation.

Analog Field Experiments: Pit and cave analogs on Earth would serve as an invaluable first step to future planetary pit and cave exploration. Science investigations at analog sites can illuminate possible morphologies and formation mechanisms for pits on the Moon, Martian moons, and asteroids. Additionally, analog experiments serve as a test case for integrating scientific concept of operations, including sensor types and measurement locations. Analogs also enable field-testing that evaluates technologies for exploring these pits and caves. The first step to such a mission would identify sites on Earth where relevant analogs exist, classify these sites with regard to their applicability as analogs, and conduct field experiments at these sites.

Prior field experiments by Astrobotic have investigated options for robotic access and modeling of pits and caves at strip mines, lava tube caves, and skylights.

Analog field-testing provides invaluable test opportunities for developing technologies for exploration and modeling and scientific approaches

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