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A Roadmap for Planetary Caves Science and Exploration

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To the Editor—2021 is the International Year of Caves and Karst (IYCK). To honor this occasion, we wish to emphasize the vast potential embodied in planetary subsurfaces. While researchers have pondered the possibility of extraterrestrial caves for more than 50 years, we have entered the incipient phase of planetary caves exploration. Caves are important because they provide records of a planetary body's history. On Mars, this may include evidence of past or even present microbial life. For the Moon and Mars, caves could protect human explorers from the harmful and inhospitable surface environment.

Our knowledge of planetary caves varies from body to body. Earth represents the most advanced level of exploration, but many unanswered questions remain. Beyond Earth, identification of possible caves is most advanced for the Moon and Mars[1], with hundreds of documented candidate cave entrances and several proposed cave mission concepts. For other planetary bodies, potential subsurface access points (SAPs) have been identified, although confirmation of cave entrances has been hampered by our inability to sufficiently resolve SAP interiors (i.e., the lack of off-nadir viewing platforms). To date, the community has cataloged 2,645 SAPs on eight planetary bodies (excluding Earth) across our solar system (Fig. 1). Additionally, numerous icy satellites contain unresolved features associated with tectonism and cryovolcanism that were not included.

To systematically advance planetary caves exploration, we propose this roadmap composed of three conceptual phases: (1) identification (orbital assets), (2) characterization (surface operations), and (3) exploration (subsurface operations).

1. Identification: Thus far, most planetary cave entrances, skylights, and collapse pits have been found by using standard remote context imaging[2]. On Earth, cave entrances are often identified via a combined thermal, visible, and lidar approach. Such strategies should be further refined and expanded to detect caves on other planetary bodies. A combination of these techniques with orbital subsurface geophysical methods including radar and gravimetrics[3] could provide optimal advances in cave identification. However, to conduct a broader, solar system wide inventory of cave candidate entrances, additional orbiting spacecraft with sensors capable of accurately resolving these features is needed.

2. Characterization: Prior to the selection of an exploration target, candidate cave entrances must be thoroughly evaluated. High resolution imagery should be acquired for promising lunar and martian cave candidates, those imagery systematically examined, and the features rank ordered by scientific importance. Additionally, current and future assets such as the Mars Ingenuity Helicopter and Titan's Dragonfly (planned for 2034) and other proposed missions (e.g., NASA Moon Diver and ESA Lunar Caves) could be used to confirm and/or examine scientifically interesting SAPs in situ. Surface missions can map cave geometries around the entrance and potentially define cave extent and volume if equipped with ground-penetrating sensors[4]. Resulting mapped cave architectures and hazards will inform mission planning and help reduce mission risk.

3. Exploration: Investment in the long lead-time robotic technologies is required to ultimately explore planetary caves. Various mission concepts have been proposed including limbed robots[5], flying robot swarms[6], tethered rovers[7], microbot swarms[8], and deployable stationary payloads[9]. Each platform has unique capabilities and limitations, and selection will depend on cave structure and scientific objectives.

Robotic and artificial intelligence (AI) technologies for cave exploration have matured significantly over the last decade[10]. These include mobility in cave terrains, autonomous navigation, node-to-node communication, and sample site selection (for life detection and habitability assessments) in aphotic conditions. While significant technological advancements have been made, several additional engineering challenges remain—especially power, access, and high-altitude entry descent and landing (EDL). Power will entail bundling within a tether, alternative internal power sources (e.g., fuel cells), or recharging by returning to the surface. Navigating complex cave architectures will involve further AI development. On Mars, most caves detected so far occur at high altitudes. Landing at altitude will require either new pinpoint EDL methods or the capability to conduct a long-distance traverse from low to high altitude regions.

Planetary caves science has the potential to significantly expand over the next decade. On Earth, analog studies and technological research and development will be imperative. The advent of aerial drones for bodies with atmospheres is a potential game-changer; these systems could be used for both detection and entrance characterization. For rovers, spaceflight-qualified instruments capable of resolving (and characterizing) cave entrances and internal structure will be indispensable.

For the Moon and Mars, a mission over the next few decades is achievable, given appropriate investment in robotic development. Specifically, to reach the technological maturity required, the platforms discussed here should be developed to flight-qualified status. By applying this roadmap and advancing these key technologies (as well as site characterizations), we will be able to investigate the planetary subsurface—one of the most promising potentially habitable environments to search for evidence of life. This, in turn, will help foster the technological developments required for human exploration and habitation of caves on the Moon and Mars.

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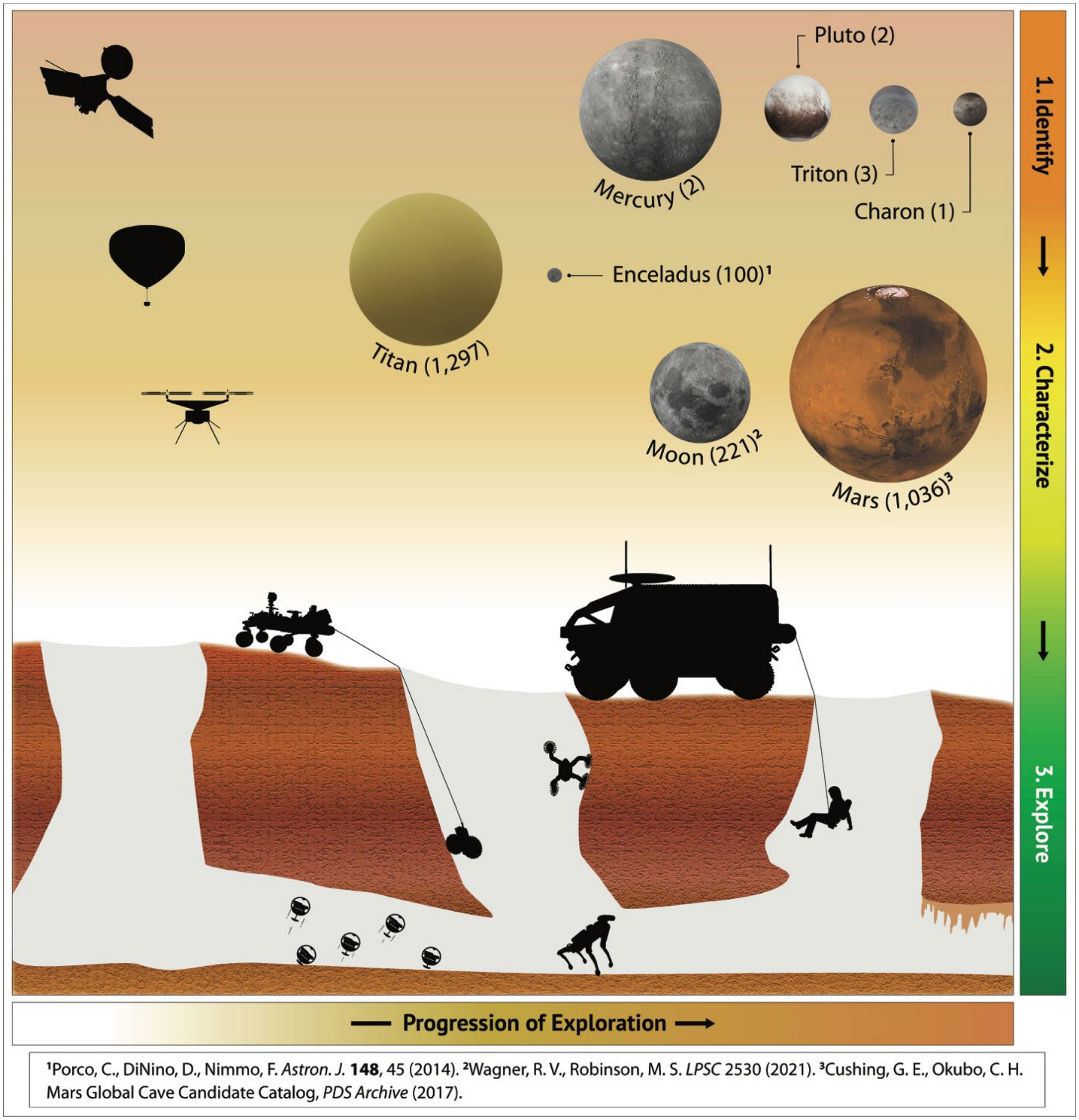

Figure 1. Planetary bodies are positioned within their respective research stage. Numbers in parentheses indicates total number of potential subsurface access points (SAPs). Barring the Moon and Mars, most planetary bodies remain within the identification stage. Given the number of potential SAPs, Titan and Enceladus fall between investigation and characterization. Orbiter and sub-orbital balloon (for bodies with atmospheres) identification and aerial drone characterization (and possibly entrance examination) advances from top to bottom. Robotic and ultimately in situ human exploration of planetary caves occurs principally along a continuum from left to right. Hopping microbots, single-axle tethered and limbed rovers are clustered together. While these robotic platforms are expected to perform similarly, robotics will be driven by mission requirements and objectives.