Introduction

Recent years have seen a rapid expansion of international participation in lunar exploration. The Moon has become a focal point for many governmental and private organisations in the areas of technology development, scientific research, human exploration and public engagement. While the surface of the Moon has been documented with high resolution cameras by several satellite missions, very little is known about the presence and nature of subsurface cavities.

In several volcanic areas of the lunar Maria, planetary geologists have identified peculiar pits that could be related to the collapse of cavities. In Marius Hills, a pit on the bottom of a shallow rille has been interpreted as the partial collapse of a lava cave (scientifically termed pyroclasts; colloquially termed lava tube) roof with a visible cavern below the overhanging ceiling [1, 2]. Gravity measurements by the mission GRAIL have revealed the probable presence of linear subsurface voids along sinuous rilles [3], while the Lunar Radar Sounder on board of the satellite Kaguya [4] has detected the presence of potential voids between 70 to 140 meters of depth in the Marius Hill region. Studies on the structural stability of lunar lava tubes in 1/6 g considering the strength characters of Maria basalts have showed that this type of cavities could theoretically reach dimensions of more than 2 km of width, 600 m of height below a roof of less than 20 meters of thickness [5].

The exploration and mapping of lava caves could provide new data on the formation of plateau basalts on the Moon, providing access to vertical sections of lava flows. Caves formed by lava flow conduits could possibly provide long-term shelter for human habitats shielded by cosmic radiation and micrometeorite impacts on the Moon. Intact, open cave segments could be suitable for housing a permanent lunar base providing potential access to several resources, including volatiles and possibly water ice trapped in cave regolith.

Space agencies have started to discuss possible mission scenario and to evaluate the necessary technology. In the view of the Artemis mission and the renewed interest on the return to the Moon, also with the Gateway as support platforms for robotic exploration, the European Space Agency has also started to develop the topic of lunar caves mission scenarios.

In order to start a European discussion on the topic involving academia and industrial partners, the European Space Agency in August 2019 opened a Campaign through its Open Space Innovation Platform, asking for novel ideas to address detecting, mapping and exploring caves on the Moon. The implementation path foreseen for this campaign are small system studies, addressing overall mission architecture design. These have maximum budget from ESA of €100 000 per activity and a maximum duration of six months. New system studies are used by ESA either as a precursor for technology developments or to assess the feasibility of systems for space. Following ESA’s SysNova technology assessment scheme, these studies serve to competitively determine the most interesting concepts among a typically relatively large number of alternative solutions, recognising the beneficial role of parallel and joint studies by both academic and industrial institutions during this exploratory phase.

For the Lunar Caves Challenge ESA plans to select about five system studies on the basis of the evaluation criteria.

Campaign Goals

In order to shape future missions to the subsurface of the Moon and to evaluate the accessibility and morphology of these cavities it is necessary to develop robotic platforms and scientific instruments that will address a number of key areas, like:

- Lunar caves detection from surface instrumentation
- Lunar caves access and exploration through robotic systems
- Lunar cave navigation and mapping
- Communication/power network from surface/orbit toward the lunar caves interior

For the ideas campaign ESA has provided a detailed description of these themes as below. Ideas submissions were required to address at least one of these themes. However, concepts that address more than one challenge theme have been highly encouraged.

Theme#1 Robotic concepts for cave access along vertical wall; in order to access volcanic cavities it is necessary to develop robotic technologies that could overcome vertical obstacles like the pit walls. Pits observed on the Moon have depth ranging from 30 to more than 100 meters, often with over hanging walls. To access the bottom of these pits and explore the void...
that generated the entrance collapse, it is necessary to develop safe systems through methods like: rappelling, tethering, anchoring, soft high-precision landing, free-falling and others.

**Theme#2 Navigation and progression inside the cave on horizontal segments;** once the bottom of the pit is accessed, it is necessary to develop robotic systems able to progress inside the cave. Lava conduits analogues on Earth show that this progression and exploration could face several natural obstacles like rock piles, loose fine sediments, crevices, giant boulders, low ceiling passages, vertical steps, etc.

These obstacles could be overcome with new robotic concepts and solutions.

**Theme#3 Cave mapping and navigation;** While exploring the cavity it is necessary, both for navigation and scientific purposes, to keep track of the surrounding environment through high-precision mapping. The lack of georeferencing systems represent a high challenge that can be overcome only with real time mapping through technologies like laser scanners, photogrammetry, inertial systems and others. Innovative solutions are necessary, including multi-robot systems or integration between surface and subsurface instruments.

**Theme#4 Communication/power network cave interior/lunar surface;** once inside the lunar cave it is necessary to keep the communication with the surface and finally with Earth. This theme focuses on how to bring the data to the lunar surface (Moon-Earth segment excluded) from a subsurface environment, including scientific and mapping data. Another problem to be addressed is the power network, since in the cave there is no possibility to directly access solar energy for battery recharge. Any innovative proposal addressing these issues will be welcome.

**Theme#4 Science payload;** the robotic system should carry any instrument that could provide scientific data regarding the environmental conditions of the lava tube, including the presence of volatiles, water ice or others. The science payload should provide to the mission the possibility to fulfil a meaningful scientific objective in the context of the overall exploration concept and the general future exploration strategy for lunar exploration.”

**System Constraints for the ideas**

The campaign is looking to mission concepts based on single rover/robot or on a distributed system of robotic/rover systems operating together to meet mission objectives.

In both system architectures, the following assumptions and constraints were required to apply to the challenge:

- A robotic/rover system shall be landed on the Lunar surface in the proximity of the Marius Hill skylight, which is situated at coordinates 14.091 N, 303.223 1E
- Each robotic/rover system landed on the surface needs to meet the physical constraints implied by existing launch and transportation systems.
- The cave detection system from the surface must be able to identify a void at a depth between 30 to 150 meters, and dimensions between 100 to 1000 m, in basaltic material.
- The robotic/rover system, or part of it, must be able to access pits to a depth of at least 50m, vertical or overhanging walls, instable pit rims (can be approached safely only up to few meters from the edge).
- The robotic/rover system accessing the cave at the bottom of the pit must be able to penetrate for at least 200 meters inside.
- The communication of data must happen from a depth of minimum 50 meters to the surface.

**Preliminary results of Sysnova Lunar Cave challenge**

A total of 34 ideas have been submitted to the call, of which 22 have been found eligible for evaluation. An Evaluation Board composed of planetary geologists, volcanologists, robotic and system engineers and mission planners have thoroughly evaluated the submissions. Eight submissions were evaluated promising and a full proposal has been requested. In the early months of 2020 the up to five selected proposals will be funded in order to develop the proposed concepts within a 6 months period. The resulting concept analyses will support ESA’s strategy for future exploration of lunar caves and promising concepts may be further developed within ESA’s Concurrent Design Facility (CDF).

**References:**