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Original Paper

Exploration of Lunar Holes, Possible Skylights of Underlying Lava Tubes, by Smart Lander for Investigating Moon (SLIM)

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The Japanese lunar orbiter SELENE discovered three giant holes, Marius Hills Hole, Mare Tranquillitatis Hole, and Mare Ingenii Hole, that exceed tens of meters in diameter and depth, and that are possible lava tube skylights. These lunar-hole structures and possibly underlying lava tubes have great significance for lunar science and potential utilization, and thus should be priority targets of future lunar exploration. It is essential to acquire detailed information on terrain around the holes, multi-layered outcrops on the inner walls of the holes, debris and thermal conditions on the floor of the holes, and entrances of predicted lava tubes extending from the bottoms of the holes. The Smart Lander for Investigating the Moon (SLIM) mission, a future Japanese lunar lander mission being considered, is planned to land in an area within 100m around the Marius Hills Hole. Rovers will be dispatched from SLIM and approach the hole. SLIM and its rovers are small but the mission return could be huge.

Key Words: Moon, Exploration, SLIM, Hole, Lava Tube

1. Introduction

In 2009, a very deep hole was discovered by SELENE Terrain Camera observation[1)]. The hole diameter and depth exceed 50m, quite unlike normal craters on the Moon (see Fig. 1 and Table 1). The hole is located within a sinuous rille formed by lava flows, a province of the Marius Hills region (Table 2) that has numerous prominent volcanic features[2)]. Haruyama et al.[1)] concluded that the hole is a possible skylight of a lava tube based on its location and a comparison with other plausible formations.

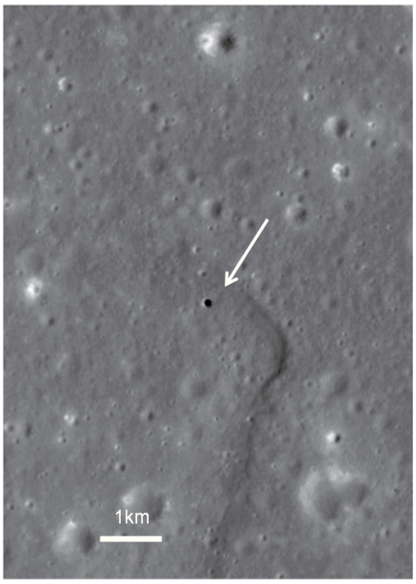

Fig. 1. The Marius Hills Hole discovered by SELENE [1)], that is located within a rille in the Oceanus Procellarum. Haruyama et al.[1)] indicated it is a possible skylight of a lava tube.

A lava tube is a subsurface conduit formed by volcanic lava flows. A typical lava tube is formed as follows. The surface of lava coming down from a volcanic vent is cooled and solidifies to become the ceiling while the lava continues to flow under the ceiling. After the lava eruption ceases, the paths and tunnel structures remain. That is a lava tube.

Lava tubes are commonly observed on the flanks of Mt. Kilauea on the Hawaiian big island, Mt. Fuji in Japan, Mt. Hara in Korea, and other areas with low viscosity basalts. The lunar mare is covered by basaltic lava. Therefore, the existence of lava tubes on the Moon has been predicted for a long time[3-6)]. Previous workers have inferred that some rilles on the Moon might be lava tubes that have been collapsed by meteorites[3-6)]. However, no lava tube entrance that would prove a lava tube had formed has been discovered[3,4)]. The hole at the Marius Hills discovered by Haruyama et al.[1)] is the first possible entrance into a lava tube.

Haruyama et al. [7)] afterward performed a global survey of the TC data set and succeeded in identifying two other holes that are larger and deeper than the Marius Hills hole (Table 1). The locations of the newly discovered holes are listed in Table 2. One is located in Mare Tranquillitatis, 300km from the Apollo 11 landing site. The other is found in Mare Ingenii on the lunar far side. While MHH is in a rille, there are no rille features around MTH or MIH. This TC data survey covers more than 95% of the lunar mare region. Therefore, these are most likely the only three lunar holes of several tens of meters to one hundred meters in diameter and depth. The location data were introduced to the Lunar Reconnaissance Orbiter (LRO) team and many images of the holes were taken by the Narrow Angle Camera (NAC) on board LRO at 0.5 to 1 meter pixel resolution[8)] (see Fig.2 for the Marius Hills Hole).

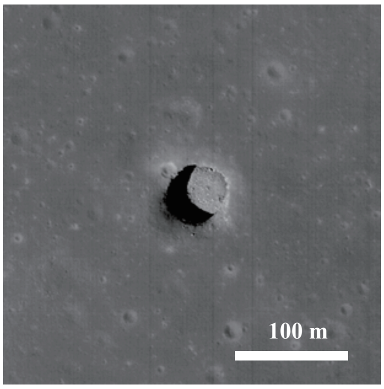

Fig. 2. An image of the Marius Hills Hole acquired by Lunar Reconnaissance Orbiter Narrow Angle Camera of 0.5 m pixel resolution (M122584310LE).

Table 1. Size of Lunar Holes.

	Axis length		Slew	Depth *1)
	long	short	Angle	
Marius Hills Hole	59 m	50 m	53°	48 m
Mare Tranquillitatis Hole	98 m	84 m	165°	107 m
Mare Ingenii Hole	118 m	68 m	36°	45 m

*1) Depth from the edges casting the shadow-sunlit boundary

Table 2. Locations of Lunar Holes.

	Latitude	Longitude	Elevation *2)
Marius Hills Hole	303.3E	14.2N	-1.65km
Mare Tranquillitatis Hole	33.2E	8.3N	-0.77 km
Mare Ingenii Hole	166.0E	35.6S	-3.62 km

*2 Elevation from the lunar mean radius of 1737.4km.

Exploration into the lunar holes and lava tubes possibly extending from the bottom of the holes will face technical challenges. Indeed, no such exploration to any lunar hole has been programmed. However, we are considering a mission that will perform a pin-point soft-landing in an area within 100m around MHH in the Smart Lander for Investigating the Moon (SLIM) mission[9].

This paper summarizes the characteristics of these gigantic lunar holes based on images taken by TC and NAC. An overview of the scientific significance and potential of the lunar holes as lunar bases will first be presented, and then the future exploration by SLIM will be discussed.

2. Characteristics of Lunar Holes

Haruyama et al.[10] estimated lengths of long and short axes of lunar giant holes to be 59m and 50m for MHH, 98m and 84m for MTH, and 118m and 68m for MIH, and depths from shadow measurements to be 48m for MHH, 107m for MTH, and 118m for MIH (Table 1). We note the depths indicated here are those from the edges casting the shadow-sunlit boundary. No ejected materials (debris, different color materials, etc.) are seen around the holes. As Haruyama et al. previously indicated[1], the holes were probably not formed by any spout of magma or gases from underground.

All the floors of lunar giant holes seems to be covered by fine sand with tens of boulders buried in it[8,10]. A small mound of fine sands is seen on the eastern portion of the MIH floor, while relatively larger boulders occupy the western portion.

While it is difficult to estimate the formation ages of these holes, the surface ages have been estimated by crater chronology to be 3.7Gyrs for MHH, 3.6Gyrs for MTH, and 3.6Gyrs for MIH[7,10]. We note that the era of 3.6Gyrs ago represents a peak of volcanic activity on the Moon[11,12]. The floor of MTH was imaged by the Multiband imager on board SELENE. A preliminary analysis of the spectral pattern seems to indicate that the floor is fresher than the surroundings.

The LRO performed oblique imaging of the holes[8], revealing the vertical walls of MHH and MTH with multiple layers and a somewhat expanded upper portion like funnels. For MHH, a photo by LRO depicts overhanging wall structures, which strongly indicates the existence of a lava tube.

The regions containing MHH and MTH are Fe- and Ti-rich. Because rocks rich in Fe and Ti have lower viscosity, we can conclude that lava tube formation in these regions was highly possible.

3. Significance in Science and Potential of Lunar Holes as Future Lunar Bases

Lunar giant holes are worth exploring from many view points of lunar science and utilization.

-Outcrops: The inner walls of lunar holes are good outcrops exhibiting multilayered structures of near-surface lava. Areas where the holes are found are key to understanding the volcanic history of the Moon. Marius Hills in the Oceanus Procellarum consists of numerous prominent volcanic features. Mare Tranquillitatis is covered by high Fe- and Ti-content basalt. Mare Ingenii in the South Pole-Aitken basin is poorer in Fe and Ti than the Procellarum KREEP Terrain but is richer in Fe, Ti, and Thorium (Th) than other regions of the lunar far side. Detailed investigation of the multilayer outcrops on the inner walls of the holes will provide the numbers, amounts, rates and intervals of magma eruptions and perhaps the compositional transitions, leading to significant information that will reveal the lunar volcanic history. In addition, the amount of solar wind protons trapped in the regolith layers sandwiched by subsurface lavas will be a clue to understanding past solar activity. Measurements of remnant magnetic moments in the lava layers will provide information of past magnetic fields and the existence of a lunar dynamo. The lack of trapped protons in the regolith layers will be supporting evidence of the existence of a past lunar dynamo, too.

-Water reservoir: As Haruyama et al. suggested[7,10], if the holes opened simultaneously with or just after the formation of surrounding surfaces and if the solar wind hydrogen flux was similar to the current flux of 4 x 10^8 /cm^2/sec, the maximum column density of the protons inside MHH would be 0.2 tons/m^2, corresponding to a water molecule density of nearly 2 tons/m^2. While most implanted protons possibly escaped from the holes

subsequently, the insides of holes are clearly better reservoirs than the surrounding lunar surfaces.

-Dust environment research field: On the lunar boundary of sunlight and shadow, there is an electric potential difference because the sunlit areas are exposed to positively charged solar wind protons. Along with the electric field induced by the potential difference, fine, negatively charged dust may migrate from shadows to sunlit areas[13]. This phenomenon probably occurs on a large scale at lunar sunset and sunrise and thus should be investigated in detail from the view points of scientific interests as well as possible impediments to long-term unmanned and manned activities. The floors of the holes where sunlight-shadow boundaries exist for a long time during the daytime are appropriate areas for researching the environment of electric fields and dust behavior.

-Potential as lunar base: Because the floors of deep holes have limited fields of view of space, they suffer fewer micrometeorite and cosmic ray bombardments, and thus are appropriate areas for constructing lunar bases. In addition, the temperature variations on the floors are mild, while wide temperatures range on the surface. Figure 3 shows simulated surface temperatures as a function of local time at a shadowed area (blue) and an illuminated area (green) in the bottom of a hole of 50 meters in diameter and depth, located in 15N (corresponding to MHH), and at a vicinity surface (red) of the hole. The bottom of the hole and the vicinity surface are assumed to be covered by a thin regolith layer of 2 cm with albedo of 0.1 and thermal emissivity of 0.9. Thermal conductivity and Heat capacity are treated as a function of temperature[14]. The temperature range at a shadowed are at the bottom of the hole is from -20degC to 30degC, very mild, while is from -170degC to 110degC at the vicinity surface.

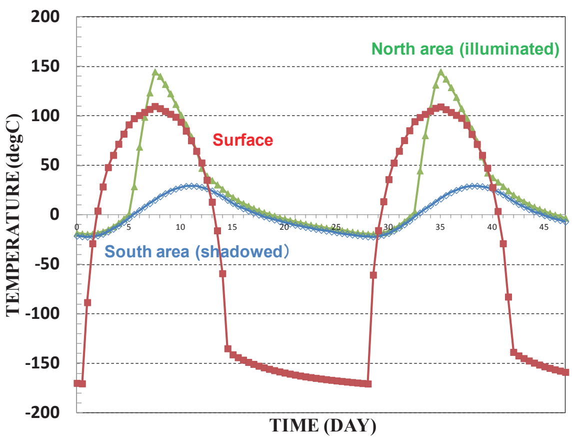

Fig. 3. Simulated surface temperatures as a function of local time at a shadowed area (blue) and an illuminated area (green) in the bottom of a hole of 50 meters in diameter and depth, located in 15N (corresponding to MHH), and at a vicinity surface (red) of the hole.

-Extending lava tube: The lunar holes strongly indicate the existence of lava tubes. The characteristics and formation process of lava tubes are of geological interest. In addition, the probably extending lava tubes will provide an excellent environment for constructing lunar bases[1,3,4,15]; the protection from meteorites and cosmic rays is perfect. The temperature is probably almost stable. The lunar tubes are expected to be wider than terrestrial ones, as large as a few hundred meters. The absence of dust, solidified and flat floors, and crystallized inner walls supposed from analogues from terrestrial lava tubes are additional advantages of lava tubes as favorable locations for constructing lunar bases.

4. Lunar Hole Exploration by SLIM

The giant lunar holes are clearly significant targets of future lunar missions, as suggested in the previous section. However, it may be too risky to try entering any holes directly. Before a hole-in-one mission, we may have to plan a path-finder mission to explore the features around the holes; SLIM is perhaps a candidate for such a mission.

We are planning to propose the SLIM mission as the third mission of a series of small science explorers[9]. The launch is planned for the mid 2010s. SLIM would weigh ~ 120 kilograms, including two rovers of 1.5 kilograms in total[9,15]. The main purpose of SLIM is to demonstrate the technology of pin-point landing on the lunar surface that will be necessary for future lunar and planetary explorations. The candidate landing point is an area within 100m around MHH.

High-resolution imaging from SLIM and its rovers is being considered but may still be difficult due to resource restrictions (weight, power, communication data rate, lifetime, etc.). However, an assessment of the surface around the landing point using imagers will be valuable. A high-resolution map would provide information of obstacles to accessing the hole from the landing sites and for constructing any infrastructures around the hole. For instance, we would want to know of any steep slopes and the distribution of meter-scale craters and rocks. The LRO's resolution of 0.5 to 1m per pixel is insufficient. The panoramic and stereo photos around the landing site would also contribute to assessing the surface around the hole. Portions of inflated ceilings of underlying lava tubes may be indicated as slightly bumpy, lengthwise features.

Rovers will be dispatched from the lander in the landing phase and begin inflating their tires[15]. After reaching the surface of the Moon, they will start moving towards the hole. The mission resources of the rovers are also very limited but image data acquired by the rovers will be highly valuable.

When the rovers reach the rim of the hole, many observations will be expected from the viewpoints described in the previous section.

- Walls: How many layers are observed with differences of materials on the inner walls? Are there thick regolith layers? Searching for an appropriate route along with inner walls from the rim to the floor will be an important mission.
- Existence of associated lava tube: Finding possible entrances to lava tubes at the bottom of the hole will clearly be one of the highest priority missions of the rovers. The inside of possible lava tubes extending from the bottom will be too dark to investigate in detail. However, detailed features of over-hanging rocks on the lower portions of inner walls and the features of the mounds on the floor of the hole will be significant information indicating the existence of underlying lava tubes.
- Floor conditions: Information of the floor, such as the distribution of boulders, amounts of regolith, temperature and

dust environment, and the possibility of implanted protons, will be valuable for science and future expeditions to the floor and a possibly extending lava tube. However, it will also be challenging and may require payload resources.

5. Conclusions

Lunar holes at Marius Hills, Mare Tranquillitatis, and Mare Ingenii discovered by the SELENE Terrain Camera are gigantic with diameters and depths of several tens to one hundred meters[7]. The holes are possible skylights of underlying lava tubes[1,7],. It is valuable from scientific viewpoints and from the potential as future lunar bases to assess the vicinity, vertical walls, and floors of the holes and to find evidence of lava tubes possibly extending from the bottoms of the holes. The lunar holes and lava tubes should be explored with high priority. We are planning the Small Lander Investigating the Moon (SLIM) mission to land within 100m around the Marius Hills Hole[9]. Two small rovers will be dispatched from the lander and try to approach the hole[15]. SLIM's main purpose is to demonstrate soft landing on the Moon. The resources of SLIM and its rovers are very limited. However, if mission instruments such as high-resolution and/or panoramic stereo cameras can be installed to acquire data on the holes and lava tubes, the mission return from SLIM will be much greater.

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