

Lunar and Martian Lava Tube Exploration as Part of an Overall Scientific Survey

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Introduction

Orbital photographic and remote sensing surveys of the Moon and Mars both show extensive evidence of lava tube formation. These natural caverns form as the result of lava flows that have over-crusted to form subsurface flowing rivers of lava; as they drain an open conduit is left behind. The scale of these caverns can be inferred from the related sinuous rilles which represent lava tubes that have collapsed and nearby craters which have clearly defined topographic features. From this we estimate that the dimensions of lunar tubes are much larger than terrestrial lava tubes. The size of these rilles and associated topographic ridges (which may represent sections of a tube that have not collapsed) suggest cross-sectional widths on the order of hundreds of meters, lengths of tens of kilometers, and roofs that are meters thick.¹

No *bona fide* intact lava tubes have been identified to the authors' knowledge. However, we do see in the photographic record numerous instances of rilles and channel-like features that show what appear to be collapsed and uncollapsed tube sections in a repeating pattern. It is important to recognize that there is general consensus that lava tubes exist on the Moon, and on Mars, but that the orbital photographic analyses that have been done are incapable of proving the existence and characteristics of any uncollapsed (ie, internally open) tubes.

The Potential Importance of Lava Tubes

Lava tubes will be important to scientists and planetary exploration architects for a number of reasons, and the effort required to discover and characterize them offers the opportunity for synergy and the multi-purposing of tools, manpower, and mission planning.

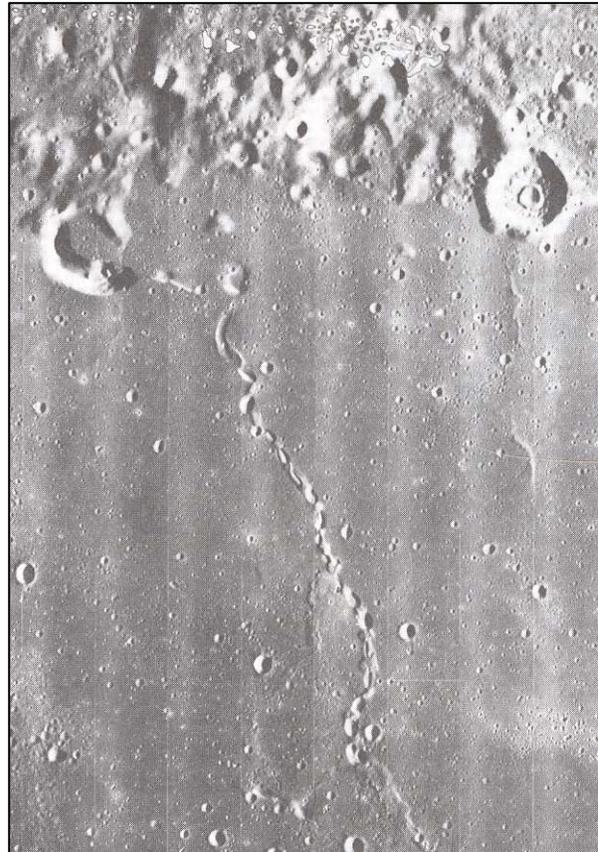


Fig 1 Lunar Lava Tube. This feature was described in detail by Oberbeck et al (1969). It is approximately 40 km in length and shows the characteristic pattern of serial collapse pits. The end of the tube is within 10-12 km of highland features. Image from Lunar Orbiter 5 Frame 182, Northern Oceanus Procellarum. Credit NASA/Lunar and Planetary Institute.

¹ Horz, Friedrich, In Lunar Bases and Space Activities of the 21st Century, W.W. Mendell, ed., 1985, Lunar and Planetary Institute, Houston, TX, pp 405-412.

To the geologist, discovering and gaining entry to a section of uncollapsed lava tube would permit direct examination of pristine bedrock, and potentially, materials brought up from depths that are inaccessible from the surface. This could show, in context, undisturbed native mineral composition as it flowed up from the lunar interior. It would be isolated from solar wind deposition and gardening, transported ejecta, asteroidal and cometary deposition, and mixing with shock-modified materials. Lava tubes are also useful in understanding the history of volcanism as well as the thermal history (heat flow) of a planet or moon.

The same bedrock would also be an ideal location to conduct seismic investigations.

The interior conditions of a lava tube are equally important to scientists and lunar base architects. With multiple meters of solid rock as cover, the interior of a lava tube provides superlative protection from solar proton event (SPE) radiation. No additional material would need to be used to provide complete protection for astronauts and various hardware on very long duration missions. Within the tube and situated some distance from the exposed tube entrance, the ambient temperature within a tube will remain constant, freeing habitat engineers from designing a structure that must cope with the extreme temperature variations that are found at the surface. And, being free of the intrusion of regolith dust, the occupants and users of a lava-tube situated habitat/lab would be largely relieved from the difficult problem of dust mitigation.

These issues are important to the establishment of an *in situ* lunar (or Martian) science laboratory. It would permit mission durations to be largely unrestricted by radiation exposure, and it would allow the use of a wider range of sensitive equipment that would otherwise be unworkable or difficult to maintain if not isolated from radiation, temperature, and dust. The implications for the economy of such missions are extensive insofar as they would allow more payload mass to be landed that is dedicated to science functions – mass that would otherwise have been required for radiation shielding and dust mitigation.

In short, if we could access a structurally sound tube – a non-trivial task, to be sure – we could dramatically redefine and expand science mission objectives.

Martian Lava Tubes

Lava tubes are believed to exist on Mars, and the environmental conditions that are believed to exist within lunar lava tubes should also be found within Martian tubes.² If life exists on Mars, one compelling place to search for it would be within a lava tube or cave.^{3,4} Here, life would be protected from ultraviolet radiation, volcanic minerals might provide a rich

² Cushing, G.E., T. N. Titus, J. J. Wynne, and P. R. Christensen, "THEMIS Observes Possible Cave Skylights on Mars," *Geophysical Research Letters*, Vol. 34, L17201, doi:10.1029/2007GL030709, 2007.

³ Boston, P., et al. (2004), "Extraterrestrial Subsurface Technology Test Bed: Human Use and Scientific Value of Martian Caves," *Space Technol. Appl. Int. Forum*, 699, 1007–1018.

⁴ Léveillé, R.J. and Datta, S. (2009). Lava tubes and basaltic caves as astrobiological targets on Earth and Mars: A review. *Planetary and Space Science*, doi:10.1016/j.pss.2009.06.004.

source of nutrients for chemosynthetic organisms (as we see on Earth near volcanic vents)⁵, and perhaps most importantly, constant temperatures maintained by internal heat might permit liquid water to persist. Secondary minerals, commonly formed in Earth caves, may also be found in Martian caves and may represent important records of past environmental conditions or even past life through preservation of biosignatures.^{6,7} Skylight entrances to possible caves or lava tubes have been noted in THEMIS imagery, but at elevations that are believed to be too high to currently support life.⁸ However, more lava tubes are likely to be unseen and unexposed by a prominent skylight at lower elevations. These conditions, all favorable for habitability, should put Martian tubes near the top of the list for future exploration sites. Innovative remote sensing and robotic exploration techniques are currently being developed and even tested in Earth caves.^{9,10}

Paradoxically, while Martian lava tubes would be superb locations for astronaut habitat shelters and could well allow for the reduction of landed payload mass, exceptional pre-cautions would need to be taken. First, we would have to rule out the existence of living organisms before intruding into these pristine enclosures. Second, it is also possible that if we were to place a habitat within a lava tube, microorganisms unavoidably brought with the astronaut crews

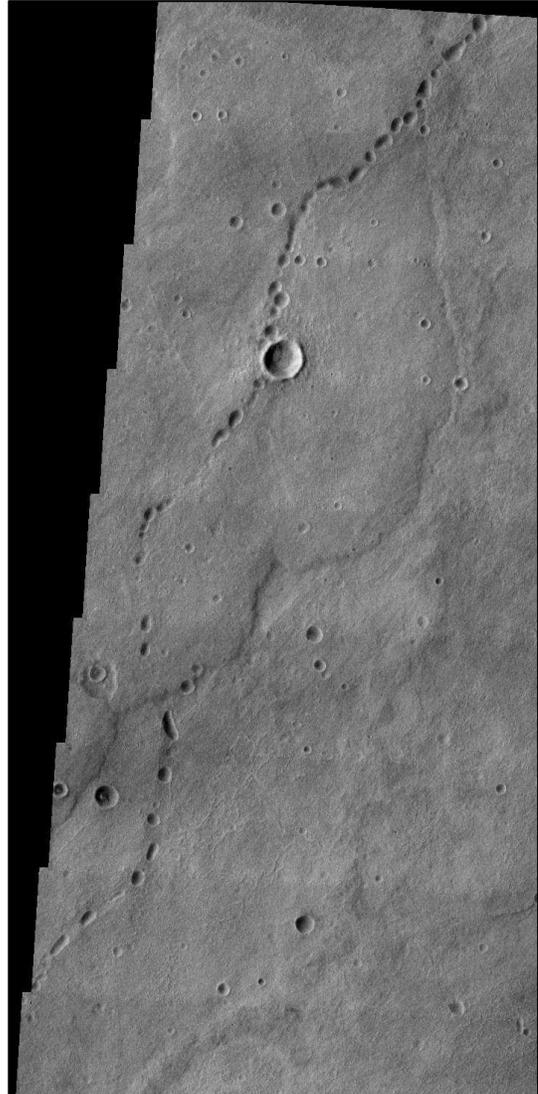


Fig 2 Possible Lava Tube on Mars. Image is from MO/THEMIS showing serial collapse pits. The sections between the pits may represent intact sections of the tube. This feature may be related to flows from Hadriaca Patera (PIA07055). Credit: NASA/JPL/Arizona State University.

⁵ P.J. Boston, M.V. Ivanov and C.P. McKay, On the possibility of chemosynthetic ecosystems in subsurface habitats on Mars, *Icarus* 95 (1992), p. 300.

⁶ P.J. Boston, M.N. Spilde, D.E. Northup, L.A. Melim, D.S. Soroka, L.G. Kleina, K.H. Lavoie, L.D. Hose, L.M. Mallory, C.N. Dahm, L.J. Crossey and R.T. Schelble, Cave biosignature suites: microbes, minerals, and Mars, *Astrobiology* 1 (1) (2001), p. 25.

⁷ Léveillé and Datta, *ibid.*

⁸ Cushing, *ibid.*

⁹ Léveillé and Datta, *ibid.*

¹⁰ Wynne, J.J., Titus, T.N., and Diaz, G.C. (2008). On developing thermal cave detection techniques for earth, the moon and mars. *Earth and Planetary Science Letters*, doi:10.1016/j.epsl.2008.04.037.

could successfully transfer to this new environment.

Implications for Lunar Base Habitat and Laboratory Design

Studies of lunar base architecture since the 1960's, and indeed, the most recent studies,¹¹ point to a small set of environmental problems that tend to drive the design. At the top of the list is radiation protection. In the absence of an artificial magnetic field generator, the only way to accomplish adequate protection from SPE radiation is by placing a substantial mass between the living organism and the external environment. Even the underside of an elevated lunar habitat requires protection from reflected secondary radiation reaction products. This directly complicates the design of the structure, the prioritization of payload deliveries, the need for water (as a potential radiation shield), and, importantly, the size of the habitat. Because the size is limited, the number of crew members is constrained, and because the radiation shield is only partially effective, dose limits for individuals mean that highly trained astronaut crew members may be restricted to only one or two missions. Similarly, electronics and test instruments that are sensitive to radiation will be more massive if they need to be hardened. All of these limitations can be mitigated by locating a habitat within a lunar cavern.¹²

The next limiting factor is temperature, which forces engineers to rely on materials and designs that are insensitive to both cryogenic temperatures and large temperature fluctuations. Constant temperatures, which are estimated to be a benign -20° C, are putatively maintained by internal heat and the insulation of the tube roof and regolith cover.¹³ This will permit simplified design of thermal management systems, and possibly liquid storage systems – both of these could result in landed payload mass reduction. Indeed, it may be possible to use the basalt walls of the tube as a heat sink to avoid the difficulty designing thermal radiators to face away from the Sun, and to keep them free of dust.

The intrusion of dust is problematic for its effects on health, and the damaging effects on technology. It forces crew to divert time to working to keep the habitat/lab clean rather than on mission objectives. They will need to regularly sweep the open surfaces of the habitat, open closed equipment housings to clear intruded dust, change out filtration and air circulation systems, spend more time on personal hygiene, and bring with them more dust-mitigation equipment. In the difficult and Spartan conditions of any lunar or Martian habitat, it is essential to limit the intrusion of dust. If however, we were able to place a habit on the hard basalt floor of a lava tube, the facility could be easily zoned away from the tube entrance and the dust.

¹¹ Beinhoff, Dallas, et al, Minimum Functionality Habitat Study, NASA, 2009.

¹² G. De Angelis, J.W. Wilson, M.S. Cloudsley, J.E. Nealy, D.H. Humes and J.M. Clem, Lunar lava tube radiation safety analysis, *Journal of Radiation Research* 43 (Suppl.) (2002).

¹³ Horz, p. 410, citing personal communication with Wendell Mendell in 1985, and also, the author has reaffirmed this estimate by personal communication with Mendell, 2006.

The Problems with Lava Tubes

There are three essential problems with this concept. The first, as stated above, is that we do not know of any *bona fide* uncollapsed tubes. To discover them, we must first conduct a careful high-resolution topographic orbital study of suspected tube locations to identify candidate sites. A follow-on surface-based exploration of these high-probability sites will need to be explored using ground-penetrating radar or other near-surface geophysical methods¹⁴ – probably using a robotic surface rover. Both of these operations however, can be combined with other necessary science missions.

The second problem is that, once located, it may be very difficult to gain access. The most obvious solution would be to locate a natural opening extending from a collapse site. It may be possible to locate such an opening from the high resolution orbital survey, if properly tasked. If such an opening exists, it is not certain that the tube will be structurally sound, or if the collapsed rubble would make entry too difficult. In the first instance, the ground penetrating radar could be important to qualifying the roof structure. Innovative robotic systems such as “cliffbots” or microbots may also be essential in initial exploration and characterization of lava tubes. It should also be remembered that the condition of this open tube has likely remained stable for millions or billions (in the case of the Moon) of years, including long periods of substantial close-proximity meteor bombardment – in fact, we see evidence of cratering along the roofs of putative open tube sections. This can be seen clearly in Lunar Orbiter 5 frame M-182 (fig. 1). The solution is to cleverly engineer equipment that can be used to clear these rock fragments – a task that seems quite within our capability. In fact, prototype lunar vehicles capable of exaction and building landing pads are already being tested in lunar analogue volcanic terrains on Earth.

The third problem is that the tube, if found, may not be located in proximity to other valuable and interesting lunar features. On the other hand, it appears that lava tubes are broadly distributed over the entirety of the lunar globe, and they occur in close proximity to mountains and non-mare areas.¹⁵ The only way to answer this issue is to conduct a search in concert with other science mission planning studies. Further study of lava tubes on Earth and a detailed search on the Moon and Mars may ultimately demonstrate that lava tubes are valuable targets for both robotic and manned exploration missions.

Conclusion

Lava tubes exist on the Moon and almost certainly on Mars. If we can locate, characterize, and gain entry to one of these caverns, very considerable advantages may be found for both scientific exploration and surface systems architecture. Due to the extreme cost

¹⁴ Haramy, K., DeMarco, M., Meglich, T.M., Hanna, K., 2004. A comparison of non-invasive geophysical methods for mapping near-surface voids. 5th Biennial Workshop Interstate Technical Group on Abandoned Underground Mines, Tuscon, AZ.

¹⁵ Horz, p 408, citing Lunar Orbiter 5 frames 182 and M-191. Frame 182 clearly shows a partially collapsed rille within 12 km of a highland region. Horz also cites the Cruikshank and Wood 1972 paper “Lunar Rilles and Hawaiian Volcanic Features: Possible Analogues,” in *Moon*, 3, 412-447.

of bringing technology to the Moon, it is quite probable that a great savings in landed mass can be accomplished by using a lava tube as a shelter for a habitat and science lab.

Such a habitat would be completely protected from radiation, extreme temperature variations, and regolith dust. The implications for logistical and mission planners are that a substantially larger fraction of the landed mass can be dedicated to life support and science mission support. This could enable longer duration missions without risk of radiation overdosing, better reliability and a more diverse set of scientific technology, and a larger habitat area in which to work. The effort required to discover and qualify a candidate uncollapsed lava tube has a high degree of synergy with other compatible science missions, and it may be possible to multi-task the same equipment for this purpose. While gaining entry to a tube may be difficult, it is within our capability.

The confirmation of Martian lava tubes would present the scientific community with a compelling opportunity as well as a quandary. Tubes and caves represent a prime location to focus the search for life, liquid water, and they would provide numerous opportunities for geological studies that could reveal much about the history of Mars. They could also provide a means of reducing the landed payload mass for manned Mars missions by providing shelter from UV radiation, wind storms, and large temperature fluctuations. However, pre-investigation of the tubes would be necessary to assure that the environment is sterile, and precautions would need to be taken to prevent the transplantation of terrestrial microorganisms.

The difficult environmental conditions that exist on the surfaces of the Moon and Mars are equally concerning to planetary scientists and habitat and surface systems designers. The existence of natural caverns on both bodies represents an opportunity to enable more ambitious planetary science investigations and the search for these features should be approached collaboratively by scientists, engineers and mission planners. There is great opportunity for multi-purposing technologies that can be used to discover these tubes and to exploit them. Lava tubes and caves should be given high priority in the planning of future exploration missions.