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A roadmap to cave dwelling on the Moon and Mars

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Abstract

Habitat in lava tubes recently discovered on the Moon and Mars, should become a unifying concept for occupancy. Basic motivations and specifications for such a habitat are briefly reviewed.

The first step is to obtain a consensus from Agencies on the validity of the concept. Afterwards, two types of research programs should be implemented:

(1) Search for lava tubes by dedicated polar orbiters.Mapping, classification and choice of site should be achieved before 2020.
(2) Development of specific technology to begin by the end of the 2020s:
 – Bulldozers, elevators, and cranes for access.
 – Inflatable cylindrical structures of large dimension for housing.

Since apprenticeship is needed for Mars habitat, Moon lava tubes would be used as a first step. Use of lava tubes provides therefore a unifying concept for exploration. A roadmap is proposed.

Keywords: Lava tube; Habitat; Mars; Moon

1. Introduction

The purpose of this paper is to suggest a plan for the study of Martian lava tubes as eventual locations of permanent settlements (Boston, 2004; Boston et al., 1992, 2001a, 2003a; Greeley, 1971, 1975; Hörz, 1995). A lava tube is a cave created when low viscosity basaltic lava flows from a non-explosive volcano. By cooling, splattering in a turbulent flow or mixing up with a more viscous lava, an empty cylindrical tube can be formed, coated with lava on the floor, walls and ceiling.

Terrestrial lava tubes, very frequent, have a diameter typically less than 15 m; on Mars and the Moon, tubes are believed to exist that are more than hundred meters in diameter, due possibly to low gravity. If smaller diameters are expected on Mars, they remain yet to be identified. A skylight is formed when a section of a cave roof has collapsed.

All linear features are not lava tubes: they can be also:

- Graben with pits, of tectonic or volcanic origin, with dimensions varying from tens of meters to kilometers.
- Craters due to secondary impacts, with dimensions varying from meters to kilometers.
- Volcanic vents created by ejection of magma through fissures, with dimensions from meters to kilometers.

On Earth, the morphology of lava tubes is characterized by:

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– Length: from a few cm to kilometers.
– Width: constant, from a few cm to meters.
– Origin: fluid lava of pahoehoe type.
– Aspect: sinuous.
– Slope: superior to 4°; larger width if slope inferior to 4°.
– Skylights: diameter inferior to the width of the tube.

On the Moon, Haruyama et al. (2009, 2012) have detected with the SELENE 10 m/pixel resolution camera a hole in the Marius Hills at 303.3°E, 14.2°N in a 48 km long sinuous rille. They estimate the hole diameter at 65 m and its depth at least 50–88 m. It would be formed in an intact lava tube with a minimum width of 370 m. An unsuccessful search for additional skylights along three other sinuous rilles nearby indicates that skylights on the Moon are rare. However, holes have also been observed in Mare Tranquillitatis and Mare Ingenii (diameters 120 and 140 m). The Marius Hills region has long been considered as an accessible exploration target, both scientifically and technically.

The NASA Lunar Reconnaissance Orbiter (LRO),[1] launched in 2008, carries a camera with 0.5–1 m/pixel resolution, which has acquired detailed images at high solar-elevation angles. From these data, the axis length of the Marius feature is estimated at 59 m by 50 m with a depth of 47 m. SELENE cameras had overestimated the depth due to their lower spatial resolution.

The LRO images of the Mare Tranquillitatis hole provide a length of the long-short axes to be 98 and 84 m and a depth up to 107 m. Both those holes are considered to be skylights of a subsurface cavern.

The Mare Ingenii hole somewhat differs from the others in that LRO images reveal an eccentric feature; the inner slope from the rim is more gradual. The long-short axes are 118 m and 68 m long respectively, the depth 47–76 m from the edge.

There are no boulders around the holes, implying there are not volcanic vents.

The survey for such holes cover more than 95% of the lunar Maria; thus such large deep holes are rare and probably limited to these three.

Cushing et al. (2007) and Léveillé and Datta (2010) have identified seven possible skylight entrances into Mars caves on the volcano Arsia Mons, dubbed the “Seven Sisters”. Using images from the Mars Odyssey Thermal Emission Imaging System (THEMIS) these features were found to exhibit diurnal temperature variations that were smaller than their surrounding surfaces.

A preliminary search around Elysium (25°N, 147°E) by Alain et al. (2012), shows evidence for the existence of 28 lava tubes, but yet without observations of skylight entrances. Some are found in the northern part of the region (30°N).

[1] Appendix A contains a table of acronyms.

The existence of lava tubes on Mars and the Moon calls for an extensive study of the value of their eventual utilization for human settlement, as has been imagined by the science fiction writer Kim Stanley Robinson in the book *Green Mars* (1994), studied by many others as Penelope Boston and advocated by the Oregon L5 Society. In 2009, the International Space University (ISU) summer program performed a design project on human habitat inside a Mars lava tube called ACCESS MARS (2009) in which quantitative estimates of the life requirements for small colonies are given.

2. When to settle on Mars and why

Human mission to Mars, when? The answer to this question was given by Werner von Braun et al. (1952) since he wrote, in the book published in 1952, that *Mankind will reach Mars in hundred years*. Well, Werner used to be right, and we will take him to his word by supposing that this event will happen in 2050 ± 5. We have forty years for planning. With the time constant of Moore’s law taken at 2 years, to be continued by nanotechnology, the performances of the electronic components will have been improved in 2050 by 8–10 orders of magnitude. Moravec (1988) in his book *Mind Children, The future of Robot and Human Intelligence* extrapolates the secular growth of computing power for a prediction of availability of human brain equivalent microcomputers around 2040. We have therefore to expect robots with near-human intelligence and high capacity communication systems. 2050 will not be 2010.

No persuasive arguments or schedule can be given for or against sending men to Mars. We take for granted that it will happen and be followed by permanent settlements.

The objective of human settlement would be:

- **National prestige** is an established driver, maybe the most powerful, but its importance cannot be assessed.
- **Exploration**: in 2050, the exploration will have progressed with a number of samples having been returned to Earth, and many robotic “visual” inspections by rovers. The need for sampling will grow in order to obtain a complete and detailed description of the past and present geology of the planet. At that time, it is to be expected that the choice of samples and the field reconnaissance will be performed as well and even better by primitive humanoids than by humans. The sample analysis will be centralized in a main laboratory situated on Mars, at the manned stations, equipped with high performance heavy instrumentation for optical, structural, chemical and isotopic studies, including search for eventual living organisms.
- **Inventory** of the soil components for various sites and depths leading to fabrication of Martian products susceptible of applications on Earth, to be obtained by local manipulation of dust, minerals, molecules and living organisms, as well as utilization of these products by the settlers on Mars.

- **Genetic engineering of viruses**, bacteria and mushrooms, is a highly debatable possibility. At that point in time this activity may be considered as necessary on Earth, but too dangerous because of possible escapes of uncontrollable species. Pursuing this research on Mars in a P-4 like environment might be a justification for human missions. Development of new genomes could lead to mass-production of modified or new organisms for utilization on Earth.

3. Why settling inside caves on Mars

Extended lifetime for missions on Mars is only sustainable if some basic requirements are met, among which we shall quote.

3.1. Safety against radiation hazards

No cost-efficient shielding totally efficient in a human mission to Mars has yet to be engineered. If on the way to the planet, the astronaut's solid waste, rich in hydrocarbons, could be wrapped around the crew quarters as it has been suggested, this makeshift could not provide a permanent solution for a large station devoted to industrial developments.

On the Martian surface, the present radiation is a combination of galactic cosmic rays, solar particle events and secondary radiation caused by the interaction of the preceding sources with atmosphere and soil (Darnell et al., 2007a,b; Simonsen and Nealy, 1991). Radiation shielding is mandatory (Saganti, 2004) since the atmosphere cannot provide adequate protection, especially during large solar eruptions which occur one to three times per solar cycle.

The total radiation absorbed by crew members was calculated (Harris, 2003) for a 540 days reference mission and found to be 14,795 mSv for a surface mission, 0.212 mSv for a cave habitat and 4,939 mSv for rover EVA during 240 h per month (the allowable dose is considered to lie between 1 and 4 Sv per year; the Severt unit, Sv, measures the biological effects of an absorbed dose; the mSv is one thousandth of a Sv).

The estimation is based on data acquired from the NASA Mars Environment Experiment (MARIE). Caves reduce background radiation to the quoted negligible value for depths around 2–3 m. A conservative value would be 5 m (Morthekai et al., 2007).

3.2. Protection against dust

Apollo missions have shown that lunar dust create risks to both crew health and EVA equipment. Dust stimulants have triggered inflammatory lesions in lungs (Chiu, 2002; Gaier, 2005). On Mars the danger would be increased by the presence of oxidants (perchlorates) in the dust. Air filtering in caves is an advantage. Protection from dust storms is obtained in caves by proper engineering of entrances. All inside structures and equipment would require less repair and maintenance than for surface habitation.

3.3. Avoidance of meteoric hazards

Mars has a higher probability of meteoric impacts than Earth (Bland and Smith, 2000; Schröder et al., 2008). Tens of meters of basalt over a lava tube would protect from most impacts and secondary fragmentation (Clifford, 1997).

3.4. Protection against extreme temperatures

Temperature in a Martian cave should stay constant near the mean annual surface temperature (around 60 °C at latitudes ±30°). Heating will be provided by a nuclear reactor (Moran and Shapiro, 2004).

3.5. Breathing space for each occupant

Paper studies of space colonies have suggested that the minimum projected area could not be lower than 50 m^2 per person for privacy and community life, plus 10 m^2 for mechanical and life support and 20 m^2 for agriculture and food processing (Cohen, 2009a,b; Heppenheimer, 1977; Johnson, 1977). The occupation of caves makes possible the deployment of ISRU (*In Situ* Resources Utilization) systems for scientific laboratories and for massive industrial production, using Martian material collected outside the caves.

3.6. Respect of international rules

The establishment of the human habitat in a closed cave will help upholding the COSPAR Planetary Protection Policy by containing human associated contaminants. Caves will be considered as "Special Regions".

4. Hazards of cave habitation

4.1. Geological instability

Lava tubes seem to have remained intact for millions of years (Coombs and Hawke, 1991). Guidelines for optimal cave assessment and selection will be developed by Earth and Moon analogue research. We have no data on Martian geological stability. The risks induced by increased human activity have been shown by comparison with experience in South Korea to be able to withstand "normal engineering loads".

4.2. Presence of Martian life

Precursor missions should assess the microbial habitability of the caves and the potential for extinct life. The eventual survival of living organisms in the lava tubes could be interesting... or deadly (Boston et al., 2001b).

4.3. Difficult access

On Earth, a vertical descent is often, but not always, required to access deeper parts of lava tubes. Boulders can also hinder entry. Numerous techniques to overcome this difficulty, the most real obstacle to the cave settlements, include cranes, escalators, ropes with pulleys and windlass, tethered balloons, microbots (McGown et al., 2002), completed by some kind of elevators or funiculars. However it is believed that, as on Earth, lava tubes could be found with dust accumulated at an entrance leading smoothly to the interior. Terrestrial examples and recent images of Martian tubes give support to this hypothesis (Richardson et al., 2009; Riedel et al., 2001).

4.4. Conclusion

In the absence of major risks occurring in cave settling, the main arguments for adopting such a solution remain the complete protection against radiation and the immediate use for habitation without excavation.

One disadvantage of the lava tubes is that they form in volcanic terrains. Search will have to be made for tubes situated at the lowest altitude possible and at the highest latitude possible (with the hope of finding subterranean ice). Syrtis Mons, Nili fossae or Mawrth Vallis are regions which could contain lava tubes and present scientific interest.

5. The station[2]

5.1. Structure

The techniques and tools required for building and accessing the station will have been developed on the Moon. The lunar phase of exploration is needed for learning how to accommodate the special features of planetary cave dwelling.

Each utilized part of the tunnel will be plugged at both ends by an airlock. Two options are open for the walls:

- They can be covered with a projection of a mixture of local regolith or dust and of material of terrestrially origin. See the abundant literature on sealing on the Moon (Cameron et al., 1990; Hatanaka and Ishida, 2004; Hatanaka and Perino, 2007; Kaplicky and Nixon, 1986; Kaplicky et al., 1992; Khalili, 1989; Lin, 1985).
- A preferred solution, well adapted to cave dwelling, is the use of inflatable structures (Campbell et al., 2002; Gormly et al., 2010; Gruber et al., 2007; Kennedy and Adams, 2000; Lowe, 2006; Petrov et al., 2006, 2010; Yin, 1989). First settlements could use 10–20 m long tubes of easy access for development and testing of inflatable habitats, with a later extension to tubes hundreds of meters in length, which could provide possible expansion up to city size. Collapsible pressurized vessels, made of a membrane-like fabric would be deployed on site. Metallic erectable structures have also been proposed for lunar bases (Eckart, 1999).

The cave settlement is completed near its entrance by a surface section which is not permanently lived in.

5.2. Power systems

The principal energy source is a nuclear reactor, situated at one extremity of the tunnel. An ESA study quotes that a 30 kW power is needed for a habitat module of a few occupants (Mars Design Mission, 2008). NASA's first Mars Reference Design Mission (Weaver and Duke, 1993) claims a need of 160 kW for covering all ground-base requirements, upgraded to 2×160 kW for redundancy (Hoffman and Kaplan, 1997). This reactor could be a SP-100, of mass 14 tons. Active heating and cooling are required in the cave. A complementary energy source would consist of large photovoltaics arrays deployed outside the tunnel.

5.3. Life support systems

Basic principles, to be established and tested first on the Moon, will be:

- Water, air and wastes of the station would be 100% recycled.
- Processing Martian CO_2 would provide O_2, CO and also CH_4 if H_2 is available. The most likely H_2 source would be imported from Earth; this will be our baseline. In the next twenty years exploration will reveal if and in which conditions H_2O can be tapped on Mars.

We will suppose settlers organized in squadrons of six people, and the station dimensioned to accommodate two squads. Each life support system will be conceived as a module for six users.

- Atmospheric management: CO_2 renewal and O_2 generation will be obtained by procedures tested on the Moon.
- H_2O regeneration: special techniques for water reclamation could be used in caves as dehumidification of Martian air, even if it would require 3 kW hour/kgH_2O (McKay et al., 1986, 1993) or recovery from cave ice (very unlikely) (Garvin, 2001).

[2] There are many publications on various aspects of a station on Mars. In addition to the specific references in this section, the following may be of interest to the reader: Belvin et al., 2006; Benaroya, 2002; Boston et al., 2002, 2003b, 2004, 2006; Cohen and Kennedy, 1997; Daga et al., 2010; Drake, 2007.

- Waste management: would not be different from surface approaches, with methods chosen as a function of mission duration and food closure (Drysdale and Maxwell, 2003; Drysdale, 2007). Residues would be sterilized, packaged and stored. Decomposable products (faeces, urine, hygiene water, etc.) would be pyrolysed for H_2O recovery, conducing by electrolysis to O_2 and H_2.
- Food supply: since open-loop dry food requirement for a 6 person crew amounts to 6.84 kg/day, a 550 day sojourn on Mars would require 3,762 kg of food (Messerschmid and Bertrand, 1999). Biogenerational approaches appear as essential to increase food closure and reduce payload transport from Earth. A subsurface greenhouse under artificial lighting is a basic part of cave dwelling. It has been computed that 40 m^2 of plant growth would produce 25% of the food mass ingested by a crew of six (Drysdale et al., 2008; Philips, 2002). Following these values, we could take 200 m^2 for producing total food mass for six people but the data of the enclosed table (taken from ACCESS Mars, 2009) lead to a surface around 1000 m^2, not unconceivable in the caves.

Plants will grow in sand, vermiculite, styrofoams or nothing with roots apparent, provided they are supported and receive nutrients. The presence of living beings other than men is crucial for the psychic equilibrium of the colonists. This agricultural section has to be regarded and treated as a garden open towards pseudo-landscapes of the Earth, with the help of holograms constantly projected on the walls in order to create a cheerful world where the real and the virtual are indiscernible (see Table 1).

Plant growing will be completed by fishponds of high yield, breeding of animals as rabbits (Gangale, 1999). It is likely that in 2050 insects will have been accepted on Earth as regular food, and they should be welcome on Mars for this purpose: an insect farm is a typical feature of Mars cave dwelling.

6. Overall architecture

Access to the cave takes place through a large skylight, maybe hundred meters in diameter, easily reached from the supposed near-by landing site. At the bottom the cave goes in two opposite directions, forming two tunnels.

One of the tunnels is devoted to housing, privacy and societal functions.

After the airlock, lies the area filled by the accommodation and regular life activities of the personnel. Further away, the laboratories, then a large section dedicated to agriculture and animal breeding.

The second tunnel is devoted to the industrial activity of the station. Here are to be found the nuclear generator of electricity and all *in situ* production of chemicals (ISRU) with recycling systems, maintenance of fuel cells and batteries, shops, storage rooms, etc.

Laboratories and working areas can be placed on either one of the two tunnels which are connected by a pressurized passage across the skylight area.

Outside the underground station and in its vicinity, important facilities are placed:

- Large solar photovoltaic array.
- Antennae for communication with Earth, Moon, sites on Mars and Martian orbiters, including optical links.
- Storage and maintenance of mobile vehicles (see below).
- Landing and take-off areas.

The deployment of the station would unfold in phases:

(i) A robotic mission would land near the chosen site, explore the morphology, deploy some system of descent support, send robots to the floor of the hole, flatten this place over a large area, and leave a localization device to help future landings. Later, a second robotic mission would land directly on the floor carrying equipment on wheels for building the first tunnel.
All equipment would be transported in modules of mass 20–30 tons.
(ii) After completion of the first tunnel and *in situ* fabrication of fuels for return, the first manned mission could land near the rim and settle in the first tunnel.
(iii) The second tunnel would be occupied and filled in the following month, the ISRU and the nuclear reactor installed.
(iv) Similar two-tunnels stations localized in other sites could be set up by various crews, some of them by robots only.
(v) Since complete autonomy of the colony is not conceivable, a permanent noria of planetary vessels, very likely moved by solar sails, would transport from

Table 1
Requirements and productivity of higher plants.

Plant requirement values		Plant performance values	
Parameter	Amount	Parameter	Amount
CO_2	40–300 g/m^2/day	O_2	30–220 g/m^2/day
Water	5–10 kg/m^2/day	Transpiration water	5–10 kg/m^2/day
Minerals	10–100 mg/m^2	Edible biomass	20–40 g/m^2/day
Lighting period	8–24 h	Inedible biomass	4–20 g/m^2/day
Lighting period	13–170 W/m^2		

Earth equipment, H_2O and H_2, and in return from Mars to Earth the products elaborated on the red planet, by commuting between Mars and Earth orbiters.

7. Mobility

It is essential in the concept of the lava-tube dwelling that fast transportation would be available outside, because far away regions have to be reached. Instead of rovers similar to trucks derived from the practice on Earth and clumsy on Mars, as presented in the literature, vehicles adapted to local conditions will be used. In the 2010s, the NASA rover *Opportunity* travelled 28 km total in six years. The range covered by the rover C*uriosity* may not be much larger. This is not acceptable for permanent settlements.

The problem of adequate shielding during roving to locations outside the tunnel must be considered in the event of an unexpected major solar event. Both human and electronic equipment must be adequately protected. Since heavy structures cannot be placed on the rover, a mapping of additional shelters (small caves...) along any projected route seems necessary.

7.1. The inflatable rover

Since the Martian soil is littered with stones of 20 cm average size, the specific dimensions of a fast rover would have to be larger than these obstacles, i.e. 2 m or more. In the 1980s the French Space Agency, CNES, studied my idea of an inflatable Martian rover with two 6 m diameter wheels. Subsequently the students of Don Hunten at the University of Arizona built a two 4 m wheeled rover (Hunten, 1988) and Jack Jones at JPL a 1.5 m wheeled tricycle (Jones, 1999). All these vehicles are basically an assembly around wheels made of a strong plastic material (it could be rubber...) inflated by ambient air with a pump.

A possible vehicle for the cave dwellers could be a tricycle made of two large rear-tyres (2.5 m diameter) and a small front-one (1.5 m diameter) held together by an aluminum structure. Motion would be provided by an electrical engine fed by a fuel cell. Two types would be used: one carrying a pilot in his space suit, seated in the open air behind the small wheel and in front of the axle joining the two large wheels; the other type, nearly identical, would be teledriven from the station, with the help of a satcom in geostationary (say areostationary) orbit. Both types would be inflated, maintained and serviced at the station. With a velocity of 30 km/h and an autonomy of 10 h, such vehicles, if piloted, would have a range of 150 km with return in one day. The teledriven rover would certainly be preferred since it would have a larger autonomy and its range could be increased by a network of caches deposited as cairns where replenishment of expendables would be performed, for instance by a prepositioned RTG.

7.2. The blimp

In Mars' atmosphere, a blimp of volume 25,000 m^3 (diameter 26 m, length 48 m), inflated with a light gas could carry at low altitude a man in his space suit, the necessary equipment and a light Jeep, moved by a propeller fitted to the same engine as used for the Rover. It could also be teledriven. The CNES balloon, built for the French–Russian Mars program had a volume of 5500 m^3. A nominal velocity of 50 km/h in zero wind, would be sufficient to navigate since the winds do not exceed 10 m/s near the ground. Distances extending to 250 km from the base can be reached with return the same day. Buoyant gas (H_2 or He) could be brought from Earth (300 kg including bottles for one blimp), but an attractive option is the use of CO locally produced from CO_2.

The recent developments of solar powered unmanned aircraft for stratospheric flights on Earth open the possibility of using planes on Mars. The take off problem could be solved with the help of tethered blimps (which could be used for routine access to the cave): both types of aerial vehicles would be complementary.

8. A new mission paradigm for Mars exploration

The planetology community strongly recommends the Mars sample return as its priority. The present paper proposes a new approach: to create a parallel program which would be a preparation to the utilization of Mars lava tubes for human habitat around the year 2050. A R and D program could be elaborated in the coming years for implementation starting around 2020, in three different areas.

8.1. Cartography of lava tubes

Whilst there is evidence for the existence of lava tubes on the Moon and Mars, direct measurements of their location, size, solidity and entrances with remote sensing will be required before robotic missions are launched.

8.1.1. Imagery

A resolution of 20 cm is needed for tube characterization. It will have to be achieved on Mars by low flying orbiters, or at least low perigee (200 km in the latitude region 30–50°), transmitting data from higher apogee. On the Moon a similar program is needed with this resolution for instance from a circular polar orbit at altitude 50 km. In comparison, the HIRISE instrument has a resolution of 1 m at Mars.

8.1.2. Thermal infrared detection

THEMIS has a spatial resolution of 100 m, insufficient for detecting a lava tube's entrance. With a Quantum Well Infrared Photodetector (QWIP), a spatial resolution of 1 m is possible from Martian orbit. The Pigwash lava flow, near Ludlow, California, USA, has been observed with this technique as a Mars analogue (Wynne et al., 2008; Titus et al., 2011). It seems that oblique imaging is a valid technique for detecting caves and cave-like structures, with detectability best accomplished with multiple images acquired at the hottest and coldest times of day. But before thermal detection can reach its potential, a detailed thermal model of a cave must be developed and tested.

8.1.3. Ground Penetrating Radar

A boundary between two electrically different materials reflects some of the radiation. Therefore a GPR can determine the roof and the floor of a cave, that means the dimensions and layout based on the timing of these reflections. There is a trade off when selecting the frequency: the higher the radar frequency, the better the radar can be focused, the better the vertical and spatial resolutions, but the smaller the penetration depth. Two GPR have been operated around Mars, SHARAD (Shallow Radar) and MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding), the first at 15–25 MHz and the second at 1–5 MHz. The first penetrates down to 100 m (vertical resolution 7 m), and the second to 500 m (vertical resolution 70 m). Their spatial resolution is of the order of 15–30 km cross track and 5–9 km along track for SHARAD. We require for cave description a penetration depth of 200 m and a spatial resolution of 50 m. Therefore, the frequency of SHARAD with a method for increasing the resolution, as a directional antenna, which is extremely costly in mass since the size of the antenna would have to be meters. It seems that the detection of caves by orbital GPR needs a lot of development, and may not be feasible.

8.1.4. Non orbital platforms

SHARAD on a balloon floating at an altitude of a few hundred meters would have the required resolution, but we would have to move the balloon to the proper area, predetermined previously, and we have no solution for this problem. An aircraft should be better suited for carrying GPR. Mars airplanes could be released from altitude after reentry and fly for one hour which could be sufficient for cave characterization over a limited area. Such a mission could be placed on a very small spacecraft, launched as a piggyback.

8.2. Access to the cave and base construction

Access is the specific problem of the cave as settlement: earth movers, bulldozers, heavy vehicles will have to be used for building an easy way of descending and ascending a height of the order of 100 m. Escalators, elevators and all the needed machinery will have to be developed for the lunar phase of the exploration, around lunar caves.

Inside the cave will be deployed inflatable structures of large dimensions for habitability. Again the development of such techniques will take place on the Moon. The Moon appears as a necessary preliminary step, which may require tens of years. Other heavy equipment, as the nuclear electricity generator, ISRU tools and all life support systems also require long duration testing on the Moon.

8.3. Life of a human community in a cave

Life on Mars will not be life on Earth. A large part of the consumables will be recycled, including excreta. We imagine that meat could be provided by insects or maggots, easy and cheap to breed. Quarters will be cramped, the landscape replaced by holograms. It will take many years to create the physiological and psychological tools which make acceptable the inherent constraints.

9. A unified strategy

9.1. The vision

Manned missions to Mars are not feasible without an apprenticeship. It has been mentioned above that the cave dwelling on Mars demands testing of equipment and methods on lunar caves.

The committee ILEWG (International Lunar Exploration Working Group) which serves as a liaison between the lunar missions of the Space Agencies, has proposed to join various efforts in a so-called "Robotic Village", after which an International Lunar Base would provide the frame of the future human occupancy of the Moon. This Base could be deployed in a lunar lava tube.

The cave dwelling practiced successively on both the Moon and Mars offers therefore a unifying concept for the exploration of the Solar System, around which a phased plan could be established and pursued. Its development and deployment on the Moon would become a major justification for the International Lunar Base, which could be implemented after the year 2030.

The International Lunar Base becomes not only the political *sine qua non* passageway to the continuation of human flights, but also the unavoidable tested of the future Martian Manned Mission.

The deployment of the lunar Robotic Village and later of the International Lunar Base will provide the opportunity to invent new rules for international cooperation in space, necessary for integrating new space powers, like China and India, into the future Martian team.

If the Lunar cave dwelling has become successful and its lessons learned, its Martian continuation can happen for two reasons: first, it will appear to the general public as a symbol of Science Power, and also it is possible that research in genetic engineering will require a remote place. We ignore the status of the world's affairs forty years from now, but without motivations there will be no Man on Mars.

9.2. The roadmap

A roadmap can be conceived for the implementation of the planetary dwelling program.

1. From now to 2020, elaboration of an international frame and efforts for acceptance by Space Agencies.

2. From 2020 to 2030: the cartography phase with a number of satellites (and maybe Mars airplanes) carrying detection missions. Simultaneously, implementation of the R and D program.
3. From 2030 to 2040: the implementation of the International Lunar Base and the development of the heavy machinery needed for the Martian caves.
4. Around 2060, human mission to Mars and implementation of an International Mars Base in caves.

Substantial work has to be performed in order to refine the sketch presented here. Since the whole venture is basically international, a first move would be for ILEWG and IMEWG to agree on the creation of a joint Cave Committee.

COSPAR could initiate the movement by requesting its Commission B (Earth, Moon and Planets) to report during the next General Assembly on the feasibility of cave dwelling for Moon and Mars habitability and to suggest an overall international road map in that direction.

It is hoped that at some time ISCEG will become interested and approve the roadmap towards cave settlement.

Plans should be made to establish similar living conditions inside an Earth cave in order to test some of the concepts, conduct psychological evaluation and even develop specific hardware. Such steps would appeal to the general public, spread the idea and generate the political thrust needed to initiate such an innovative program. The Biosphere project could organize such a venture.

Appendix A

Table A1

Acronyms used in this manuscript.

ACCESS MARS	Name of ISU project, 2009
CNES	Centre National d'Études Spatiales
COSPAR	Committee of Space Research
EVA	Extravehicular Activity
ESA	European Space Agency
GPR	Ground Penetrating Radar
HIRISE	High Resolution Imaging Science Equipment
HUMEX	Human Exploration
ILEWG	International Lunar Exploration Working Group
IMEWG	International Mars Exploration Working Group
ISCEG	International Space Exploration Coordination Group
ISRU	*In Situ* Resources Utilization
ISU	International Space University
JPL	Jet Propulsion Laboratory
LRO	Lunar Reconnaissance Orbiter
MARIE	Mars Radiation Environment Experiment
MARSIS	Mars Advanced Radar for Subsurface and Ionosphere Studies
NASA	National Aeronautics and Space Administration
QWIP	Quantum Well Infrared Photodetector
RD	Research and Development
RTG	Radioisotopes Thermal Generator
SHARAD	Shallow Radar
THEMIS	Thermal Emission Imaging System

References

ACCESS MARS, 2009. Assessing Cave Capabilities – Establishing Specific solutions, Final Report. International Space University (ISU Publications/Student Reports).

Alain, G., Costard, F., Marmo, C., 2012. Private Communication.

Belvin, W.K., Watson, J.J., Shingal, S.N., 2006. Structural concepts and materials for lunar exploration habitats (AIAA 2006-7338). In: 2nd International Space Architecture Symposium (SAS 2006), AIAA Space 2006 Conference & Exposition, San Jose, Calif.

Benaroya, H., 2002. An overview of lunar base structures: past and future. (AIAA 2002-6113). In: 1st Space Architecture Symposium (SAS 2002), Houston, Texas.

Bland, P.A., Smith, T.B., 2000. Meteorite accumulations on mars. Icarus 144 (1), 21–26.

Boston, P.J., 2004. Extraterrestrial caves. In: Gunn, John (Ed.), Encyclopedia of Cave and Karst Science. Fitzroy-Dearborn Publishers Ltd., London, UK, pp. 355–358.

Boston, P.J., Ivanov, M.V., McKay, C.P., 1992. On the possibility of chemosynthetic ecosystems in subsurface habitats on Mars. Icarus 95, 300–308.

Boston, P.J., Welch, S.M., Thompson, S.L., Werker, J., Frederick, R.D., Hildreth-Werker, V., Sprungman, B., 2001a. Extraterrestrial Caves: Science, Habitat, and Resources, Final Report for NIAC CP 99-03, Phase I.

Boston, P.J., Spilde, M.N., Northup, D.E., Melim, L.A., Soroka, D.S., Kleina, L.G., Lavoie, K.H., Hose, L.D., Mallory, L.M., Dahm, C.N., Crossey, L.J., Schelble, R.T., 2001b. Cave biosignature suites: microbes, minerals and mars. Astrobiol. I 1, 25–56.

Boston, P.J., Frederick, R.D., Welch, S.M., Werker, J., Meyer, T.R., Sprungman, B., Hildreth-Werker, V., Murphy, D.L., Thompson, S.L., 2002. Human Utilization of Subsurface Extraterrestrial Environment. Final Report for NIAC CP 01–01, Phase II.

Boston, P.J., Frederick, R.D., Werker, J., Welch, S.M., Meyer. T.R., Sprungsman, B., Hildreth-Werker, V., Thompson, S.L., Murphy, D., 2003a. Human Utilization of Subsurface Extraterrestrial Environment: Final Report, Complex System Research Inc., 47–53.

Boston, P.J., Frederick, R.D., Welch, S.M., Werker, J., Meyer, T.R., Sprungman, B., Hildreth-Werker, V., Thompson, S.L., Murphy, D.L., 2003b. Human utilization of subsurface extraterrestrial environments. Gravitational Space Biol. Bull. 16 (2), 121–131.

Boston, P.J., Frederick, R.D., Welch, S.M., Werker, J., Meyer, T.R., Sprungman, B., Hildreth-Werker, V., Thompson, S.L., 2004. Extraterrestrial subsurface technology test bed: human use and scientific value of Martian caves, Space Technology & Application Forum 2003 Bulletin AIP #654, American Institute of Physics, College Park, Md.

Boston, P.J., Hose, L.D., Northup, D.E., Spilde, M.N., 2006. The microbial communities of sulfur caves: a newly appreciated geologically driven system on Earth and potential model for Mars. In: Harmon, R. (Ed.), Karst Geomorphology, Hydrology, & Geochemistry Geological Society of American Special Paper 404, pp. 331–344.

Von Braun, Werner, Ley, Willy, Whipple, Fred L., Kaplan, Joseph, Haber, Heinz, Schachter, Oscar, 1952. Across the Space Frontier. The Viking Press, Cornell University, Ithaca, NY.

Cameron, E.A., Duston, J.A., Lee, D.D., 1990. Design of Internal Support Structures for an Inflatable Lunar Habitat (NASA CR-189996). Washington, DC.

Campbell, A., Barido, R., Knudsen, J., MacKnight, A., Lerner, R., Heppel, P., Dalland, T., Jarvis, C., Raines, T., Trevino, L., 2002. Advanced inflatable airlock system for EVA (SAE 2002-01-2314). In: 32nd International Conference on Environmental Systems (ICES), Society of Automotive Engineers, San Antonio, Texas, Warrendale, Pa.

Chiu, W., 2002. Pulmonary toxicity of simulated lunar and Martian dusts in mice: histopathology 7 and 90 days after intratracheal instillation. Inhalation Toxicol. 14 (9), 901–916.

Clifford, S., 1997. Lava tubes and their potential at base sites for human exploration of Mars. Available at <http://www.argoverse.com/LAVATUBE.html>.

Cohen, M., 2009a. Comparative configurations for lunar lander habitation. Volumes 2005–2008 (SAE 2009-01-2366). In: 39th International Conference on Environmental Systems (ICES), Society of Automotive Engineers, Savannah, Georgia, USA, Warrendale, Pa.

Cohen, M.M., Kennedy, K.J., 1997. Habitats and surface construction technology and development roadmap. Noor, A., Malone, J. (Eds.), Government Sponsored Programs on Structures Technology (NASA CP-97-206241), Washington, DC, pp. 75–96.

Cohen, M., 2009b. From apollo lm to altair: design, environments, infrastructure, missions, and operations (AIAA 2009-6404). In: AIAA Space 2009 Conference & Exposition, Pasadena, California.

Coombs, C., Hawke, B., 1991. On Hawaiian and Lunar lava tubes. In: Lunar and Planetary Science Conference XXII, Lunar and Planetary Institute, Houston, Texas, pp. 239–240.

Cushing, G.E., Titus, T.N., Wynne, J.R., Christensen, P.R., 2007. Possible cave skylights on mars. Lunar and Planetary Science, XXXVIII, [Abstract Number 1371].

Daga, A., Schneider, I., Uzman, Z., B., de Leon, P., Harris, G., 2010. Habitat architecture concept definition for 'Integrated strategies for the human exploration of the Moon and Mars' (A NASA-funded Study): Interim Status Report (AIAA 2010-6072). 40th International Conference on Environmental Systems (ICES), Barcelona, Spain.

Darnell, L.R., Desorghet, L., Ward, J.M., Coates, A.J., 2007a. Modelling the surface and subsurface Martian radiation environment: implications for astrobiology. Geophys. Res. Lett. 34, L02207. http://dx.doi.org/10.1029/2006GL027494.

Darnell, L.R., Desorghet, L., Ward, J.M., Coates, A.J., 2007b. Martian sub-surface ionising radiation: biosignatures and geology. Biogeosci. Discuss. 4, 455–492.

Drake, B.G., 2007. From the Moon to Mars: The things we most need to learn at the moon to support the subsequent human exploration of mars. Lunar Exploration Analysis Group (LEAG) Workshop on Enabling Exploration, The Lunar Outpost and Beyond, Houston, Texas.

Drysdale, A., 2007. How many life support system do we need. In: 37th International Conference on Environmental Systems (ICES), Chicago, Ill.

Drysdale, A., Maxwell, S., 2003. Waste system implications for Mars missions. Adv. Space Res. 31 (7), 1791–1797.

Drysdale, A., Nakamura, T., Yorio, N., Sager, J., Wheeler, R., 2008. Use of sunlight for plant lighting in a biogenerative life support system – equivalent system mass calculations. Adv. Space Res. 42 (12), 1929–1943.

Eckart, P., 1999. The Lunar Base Handbook: An Introduction to Lunar Base Design, Development, and Operations. McGraw-Hill Higher Education, New York.

Gaier, James R., 2005, The effects of Lunar dust on EVA systems during the Apollo missions, NASA/TM-2005-213610, Glenn Research Center.

Gangale, T., 1999. Rabbits on Mars: one giant leap, in on to Mars: colonizing a new world. Zubrin, R., Crossman, F. (Eds.), 2nd International Convention of the Mars Society, Apogee Books, Boulder, Colo, Burlington, Ontario, Canada. (on CDROM version).

Garvin, Jim, 2001, Water as a geologic resource in support of planetary exploration, Presentation at Annual Meeting of the Geological Society of America, November, 2001, Session 109. Abstract at <https://gsa.confex.com/gsa/2001AM/finalprogram/abstract_27033.htm>.

Gormly, S., Flynn, M., Polonsky, A., 2010. Membrane based habitat wall architectures for life support and evolving structures (AIAA 2010-6073). In: 40th International Conference on Environmental Systems (ICES), Barcelona, Spain.

Greeley, R., 1971. Observations of actively forming lava tubes and associated structures in Hawaii. Mod. Geol. 2, 207–223.

Greeley, R., 1975. The significance of lava tubes and channels in comparative planetology. In: LPI: The Conference on Origin of Mars Basalts and their Implications for Lunar Evolution, Houston Lunar Science Institute, pp. 53–55.

Gruber, P., Häuplik, S., Imhof, B., Özdemir, K., Waclavicek, R., Perino, M.A., 2007. Deployable structures for a human lunar base. Acta Astronaut. 61 (1), 484–495.

Harris R.A., (Ed.), HUMEX: Study of the Survivability of Humans to Long Duration Interplanetary and Planetary Environments. ESA SPR 64, 2003.

Haruyama, J., Hioki, K., Shirao, M., et al., 2009. Observation of possible lava tube skylights by SELENE cameras. Geophys. Res. Lett. 36, 21206.

Haruyama, J., Morota, T., Kobayachi, S., Sawai, S., Lucey, P., Shirao, M., Vishino, M., 2012. Lunar holes and lava tubes as resources for Lunar science and exploration. In: Badescu, V. (Ed.), Moon. Springer Vg, Berlin-Heidelberg, pp. 139–163.

Hatanaka, N., Ishida, T., 2004. Hydration reaction and strength development of lunar concrete under vacuum condition (SAE 2004-01-2270). In: 34th International Conference on Environmental Systems (ICES), Society of Automotive Engineers, Colorado Springs, Colo, Warrendale, Pa.

Hatanaka, N., Perino, M.A., 2007. Lunar concrete radiation shielding production for primary lunar base (SAE 2007-01-3057). In: 37th International Conference on Environmental Systems (ICES), Society of Automotive Engineers, Chicago, Ill, Warrendale, Pa.

Heppenheimer, T.A., 1977. Colonies in Space. Stackpole Books, Mechanicsburg, PA.

Hoffman, S., Kaplan, D., 1997. Human Exploration of Mars: the Reference Mission for the NASA Mars Exploration Study Team. NASA Special Publication 6107. NASA Johnson Space Center, Houston, Texas.

Hörz, F., 1995. Lava tubes: potential shelters for habitats. Lunar Bases and Space Activities of the 21st Century, ESA pub, SPR 64, 405–412.

Hunten, D., 1988. The mars ball project, Technical Report edited by P.E. Geissler. Lunar and Planetary Lab., University of Arizona.

Johnson, R., 1977. Space settlements: a design study. NASA SP413.

Jones, J., 1999. Inflatable rovers for planetary applications. In: SPIE Mobile Robots Conference.

Kaplicky, J., Nixon, D., 1986. A surface-assembled superstructure envelope system to support regolith mass-shielding for an initial-operational-capability lunar base. In: Mendell, W. (Ed.), Lunar Bases and Space Activities of the 21st Century (375–380). Symposium, Lunar and Planetary Institute, Washington, DC, Houston, Texas, pp. 275–279.

Kaplicky, J., Nixon, D., Wernick, J., 1992. Vertical regolith shield wall construction for lunar base applications. In: Mendell, W. (Ed.), The Second Conference on Lunar Bases and Space Activities of the 21st Century (NASA CP-3166, 275–279), Lunar and Planetary Institute, Houston, Texas.

Kennedy, K.J., Adams, C.M., 2000. International space station (ISS) TransHab: an inflatable habitat. In: Johnson, S., Chua, K., Galloway, R., Richter, P. (Eds.), Space 2000. 7th International Conference and Exposition on Engineering, Construction, Operations, and Business in

Space, American Society of Civil Engineers, Albuquerque, N. M. Reston, Va, pp. 89–100.

Khalili, E.N., 1989. Lunar structures generated and shielded with on-site materials. J. Aerosp. Eng. 2 (3), 119–129, Reston, Va.: American Society of Civil Engineers.

Léveillé, R.J., Datta, S., 2010. Lava tubes and basaltic caves as astrobiological targets on Earth and Mars: a review. Planet. Space Sci. 58 (4), 592–598, Special Issue.

Lin, T.D., 1985. Concrete for lunar base construction. In: Mendell, W. (Ed.), Lunar Bases and Space Activities of the 21st Century. Houston, Lunar and Planetary Institute, pp. 381–390.

Lowe, J.D., 2006. How to make an anchor-free, flat-floor inflatable habitat for the Moon or Mars (SAE 2006–01-2100). 36th International Conference on Environmental Systems (ICES), Society of Automotive Engineers, Norfolk, Va., Warrendale, Pa.

Mars Design Mission, Strategy and Architecture Office. ESA, 2008.

McGown, R., York, C., Billings, T., Walden, B., 2002. Lava tube entrances amelioration on the Moon and Mars. Space 2002 and Robotics 2002. Albuquerque, NM.

McKay, C.P., Meyer, T.R., Boston, P.J., 1986. Mars base infrastructure. In: Welch, S.M., Stoker, C.R. (Eds.), The Case for Mars: Concept Development for a Mars Research Station, JPD Publication 86–28, Jet Propulsion Lab., Pasadena, CA, pp. 95–108.

McKay, C.P., Meyer, T.R., Boston, P.J., Nelson, M., MacCallum, T., Gwynne, O., 1993. Utilizing Martian resources for life support. In: Lewis, John S. (Ed.), Resources of Near Earth Space, Mildred Shapley Matthews, and Mary L. Guerrieri, Tucson, AZ, University of Arizona Press, pp. 819–843.

Messerschmid, E., Bertrand, R., 1999. Space Stations Systems and Utilization. Springer Vg, Stuttgart, NY.

Moran, M., Shapiro, H., 2004. Fundamentals of Engineering Thermodynamics. John Wiley and Sons, Hoboken, NJ.

Moravec, Hans., 1988. Mind Children. The Future of Robot and Human Intelligence. Harvard University Press, Cambridge, Mass.

Morthekai, P., Jain, Mayank, Dartnell, L., Murray, A.S., Bøtter-Jensen, Lars, Desorgher, L., 2007. Modeling of the dose-rate variations with depth in the Martian regolith using GEANT4. Nuclear instruments and methods. Phys. Res. Sect. A Accelerator Spectrometer Detectors Associated Equip. 580 (1), 667–670.

Petrov, G., Adams, C.M., Steinfeld, K., Jajich, D., 2006. Constraints driven design of a surface inflatable habitat module (SAE 2006-01-2101). In: 36th International Conference on Environmental Systems (ICES), Society of Automotive Engineers, Norfolk, Va., Warrendale, Pa.

Petrov, G., Park, K., Adams, C.M., 2010. Optimization of inflatable spacecraft interior volume using constraints driven design (AIAA 2010-6070). In: 40th International Conference on Environmental Systems (ICES), Barcelona, Spain.

Philips, V., 2002. Lighting for Horticultural Applications. Philips Edition, Netherlands.

Richardson, P.W., Bleacher, J.E., Glaze, L.S., Baloga, S.M., 2009. The relationship between lava fans and tubes on Olympus Mons in the Tharsis region. Lunar and planetary science. In: 40th Lunar and Planetary Science Conference. [Abstract Number 1527].

Riedel, S.J., Sakimoto, S.E.H., Bradley, P.A., Dewet, A., 2001. Lava tubes flow models at Alba Patera, Mars: topographic constraints on eruption rate. Lunar and planetary science. In: 32nd Lunar and Planetary Science Conference. [Abstract number 1954].

Robinson, K.S., 1994. Green Mars. (Part 3–6, Tariqat), trade ed. Bantam Books, New York.

Saganti, P., 2004. Radiation climate map for analyzing risks to astronauts on the Mars surface from galactic cosmic rays. Space Sci. Rev. 110 (1), 143–136.

Schröder, C., Rodionov, D.S., McCoy, T.J., et al., 2008. Meteorites on Mars observed with the Mars explorer rovers. J. Geophys. Res. Planets 113 (E6), E06522.

Simonsen, L.C., Nealy, J.E., 1991. Radiation protection for human missions to the Moon and Mars. NASA Technical Publication, 3079.

Titus, T., Wynne, J.J., Jhabvala, M.D., Cushing, G.E., Shei, P., Cabrol, N.A., 2011. Cave detection using oblique thermal imaging. In: First International Planetary Cave Research Workshop, National Cave and Karst Research Institute, Carlsbad, NM.

Weaver, David B., Duke, M., 1993. NASA Mars Reference Design Mission. AIAA, 93–4212.

Wynne, J.J., Titus, T., Chong Diaz, G., 2008. On developing thermal cave detection techniques. Earth Planet. Sci. Lett. 272, 240–250.

Yin, P.K., 1989. A preliminary design of interior structure and foundation of an inflatable Lunar habitat (NGT 44-001-800). In: Proceeding of the NASA/ASEE Summer Faculty Fellowship Program, Washington, DC, pp. 26.1–26.10.