

Hypothesis Paper

Venus, Mars, and the Ices on Mercury and the Moon: Astrobiological Implications and Proposed Mission Designs

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ABSTRACT

Venus and Mars likely had liquid water bodies on their surface early in the Solar System history. The surfaces of Venus and Mars are presently not a suitable habitat for life, but reservoirs of liquid water remain in the atmosphere of Venus and the subsurface of Mars, and with it also the possibility of microbial life. Microbial organisms may have adapted to live in these ecological niches by the evolutionary force of directional selection. Missions to our neighboring planets should therefore be planned to explore these potentially life-containing refuges and return samples for analysis. Sample return missions should also include ice samples from Mercury and the Moon, which may contain information about the biogenic material that catalyzed the early evolution of life on Earth (or elsewhere). To obtain such information, science-driven exploration is necessary through varying degrees of mission operation autonomy. A hierarchical mission design is envisioned that includes spaceborne (orbital), atmosphere (airborne), surface (mobile such as rover and stationary such as lander or sensor), and subsurface (*e.g.*, ground-penetrating radar, drilling, etc.) agents working in concert to allow for sufficient mission safety and redundancy, to perform extensive and challenging reconnaissance, and to lead to a thorough search for evidence of life and habitability. **Key Words:** Venus—Mars—Mercury—Moon—Mission design—Terrestrial planets—Life—Inner Solar System. *Astrobiology* 5, 778–795.

INTRODUCTION

IN TERMS OF PLANETARY EXPLORATION, we are at a threshold. Observations from Earth-based telescopes, the Hubble Space Telescope, and space missions have provided an initial “reconnais-

sance-based” understanding about the environments of the inner planets in the Solar System. We are now transitioning into a mode of autonomous exploration that has the potential to improve our understanding of the evolutionary histories of the terrestrial planets (including ge-

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ology, paleohydrology, and paleoclimatology) and answer the question as to whether life had an opportunity to gain a foothold on our neighboring planets. An initiative has emerged, targeting the creation of spacecraft that have the capability to operate on their own, such that expanded science-driven missions loom on the near-term horizon. An objective of these missions is to design them to hone in on targeted regions with features of scientific interest to better understand environmental conditions (*e.g.*, geology, hydrology, climate, etc.) of the terrestrial planets that neighbor the Earth and evaluate their potential for harboring life, both as a place where life could have originated independently from Earth and as a potential location for future colonization.

THE POTENTIAL FOR LIFE ON THE TERRESTRIAL PLANETS

Given that the search for life is linked directly to the search for water, the study of the history of water on the terrestrial planets is appropriate for tracking planetary habitability. Distance from the Sun, planet size, composition, and variations in internal heat energy, which includes efficiency of release to the surface through space and time, are different for each of the terrestrial planets and affect the planet's suitability for the origin and persistence of life. The likelihood that liquid water was present on the surfaces and in the subsurfaces of Mercury, Venus, Moon, and Mars in the past, the nature of the climatic and atmospheric changes these planets have undergone, and the different atmospheres of present-day Venus and Mars provide exciting potential for harboring fossilized and extant life in more than one world of the inner Solar System.

Plate tectonics or some other effective recycling mechanism for minerals and nutrients is a requirement for the persistence of living systems (*e.g.*, Schulze-Makuch *et al.*, 2002a). Nutrients and minerals are otherwise quickly exhausted, and evolving life, especially that which is at a metabolically primitive state, will not be able to meet its nutrient demands. On Earth and possibly early Mars, the recycling mechanism was plate tectonics (Sleep, 1994; Connerney *et al.*, 1999; Baker *et al.*, 2002a,b; Fairén *et al.*, 2002). Plate tectonics on Earth produces greenhouse gases that act as a

global thermostat and provides stability for the evolution of life (Ward and Brownlee, 2000).

The presence of water and a recycling mechanism are limiting factors for the continued habitability of a terrestrial planet once life has originated. If, in addition, basic nutrients, light as an energy source, and/or shielding from UV radiation is available, life can become a global phenomenon rather than one that is restricted to specific niches.

Venus

Current conditions at the venusian surface are extremely desiccating and prohibitive in terms of extant life. However, the origin of life on the venusian surface early in its history is feasible. Venus formed in the same general region of the Solar System as Earth, and thus abundant solar energy and primordial waters on early Venus can be assumed. Evidence for a proto-ocean was advanced by: (1) Donahue *et al.* (1982), because of the venusian enhanced D/H ratio; (2) Abe and Matsui (1988), based on the evolution of an H₂O-CO₂ atmosphere; (3) Matsui and Tajika (1991), because of the amount of ⁴⁰Ar in the present venusian atmosphere; and (4) Pollack (1991), based on comparative analyses of the similar amounts of CO₂ and N₂ in the near-surface volatile reservoirs of Venus and Earth.

The early venusian ocean was likely a hot sea (Kasting, 1989) that eventually evaporated during a runaway moist greenhouse effect. How long the ocean or oceans were present is a controversial matter. Hydrodynamic escape and a strong solar wind could have eroded the early venusian ocean quickly (Kasting and Pollack, 1983; Donahue and Hartle, 1992; Chassefiere, 1996, 1997a,b; Lundin *et al.*, 2004). On the other hand, it has been argued that the ocean or oceans could have been present on Venus for billions of years (Marov and Grinspoon, 1998), and that significant scattering of sunlight back to space by marine stratus clouds could have cooled the surface and helped to delay a runaway greenhouse effect over a considerable period of geological time (D.C. Catling, personal communication, 2004). Jones and Pickering (2003) claimed that the venusian canals were carved by water and match key morphological features of modern fluvial and submarine channels on Earth, and concluded that surface water bodies and an associated water cycle could have been lost as late as 0.5–1.0 billion years ago.

Regardless of the timing, given the apparently rapid rise of life on Earth due, at least in part, to abundant surface water along with dynamic endogenic-driven activity, there is the possibility that life originated on Venus.

It is also possible that organisms delivered by meteorites from early Earth or Mars may have found a suitable habitat on early Venus. Experiments have shown that bacteria can survive space travel, including lift off from the place of origin and re-entry into a planetary atmosphere (e.g., Horneck and Rettberg, 2002). Theoretical considerations and modeling studies support the possibility of a transfer of microorganisms within the inner Solar System by asteroidal and cometary impacts (Davies, 1996; Gladman *et al.*, 2005). Unfortunately, any fossil record of the venusian history is unlikely to be preserved because of endogenic activity about 700 million years ago that resurfaced most, if not all, of the planet (Strom *et al.*, 1994).

Though current conditions on the surface of Venus are extremely desiccating, water may still be abundant in the planet's subsurface, perhaps in a liquid state. Liquidus curves with respect to pressure and temperature indicate that little additional pressure would be necessary (such as from overlying rocks) for fluid H₂O to occur. However, this water would be in a supercritical state with properties quite different from thermodynamically stable water, and the stability of macromolecules at such high pressures and temperatures is questionable (Schulze-Makuch and Irwin, 2002). Also, thermal disequilibria, necessary for life processes, would be rare at these high temperatures, and any organism would be in danger of thermal decomposition. Thus, although an energy source (volcanic activity) and fluid (albeit supercritical) water may be present, life probably is not.

If life gained a foothold on Venus when surface conditions were more benign, life could have retreated progressively into ecological niches through directional selection during the period of greenhouse warming (Schulze-Makuch and Irwin, 2002). One principal niche would have been the subsurface (discussed above), and the other the atmosphere. Whether adaptation to an atmosphere as an ecological habitat can occur is unclear. However, if the runaway moist greenhouse effect occurred gradually rather than catastrophically, adaptation to life in a thick and nutrient-rich atmosphere appears feasible. Today's atmospheric

conditions are controlled by an efficient carbon dioxide–water greenhouse effect and by the radiative properties of the global cloud cover, which are both sensitive to perturbations in abundance of atmospheric water and sulfur gases (Bullock and Grinspoon, 2001).

A number of arguments have been advanced in support of the possibility of microbial life in the venusian atmosphere. The following observations are of significance to the plausibility of such life: (1) the clouds of Venus are much larger, more continuous, and stable than the clouds on Earth; (2) the atmosphere is in chemical disequilibrium, with H₂ and O₂, and H₂S and SO₂, coexisting; (3) the lower cloud layer contains nonspherical particles comparable in size to microbes on Earth; (4) conditions in the clouds at 50 km in altitude are relatively benign, with temperatures of 300–350 K, pressure of 1 bar, and a pH of about 0; (5) the super-rotation of the atmosphere enhances the potential for photosynthetic reactions; (6) an unknown absorber of UV energy has been detected in the venusian atmosphere; and (7) while water is scarce on Venus, water vapor concentrations reach several hundred ppm in the lower cloud layer (Schulze-Makuch *et al.*, 2004b).

In addition, Cockell (1999) pointed out the availability of trace compounds in the venusian atmosphere that are needed for life, such as carbon, nitrogen, and phosphorus, which are derived from geochemical reactions on the venusian surface and volcanic activity. A P-bearing substance detected in the lower cloud base is presumed to be phosphoric acid derived from phosphorus anhydrite (Andreichikov, 1987). For Earth, rain and fog water rich in nutrients provide a suitable transient habitat for microorganisms (Herlihy *et al.*, 1987; Fuzzi, 2002), which supports the hypothesis that bacteria could exist in cloud aerosols (Gislén, 1948). Also, carbonyl sulfide (COS), the second most common sulfur compound in the venusian atmosphere, which on Earth is typically associated with biological activity, was recently shown to mediate the prebiotic formation of peptides from amino acids under mild conditions in aqueous solution (Leman *et al.*, 2004).

The major problems microbial life would have had to overcome to survive in the venusian atmosphere would be the lack of water, the low pH, and the large amounts of UV radiation the venusian atmosphere receives. If microbial organisms had developed a mechanism by which to assim-

ilate water vapor from hydrated sulfur compounds or from the atmosphere, similar to the assimilation of carbon from CO₂ by microbes in the atmosphere of Earth, they may have overcome the problems posed by the lack of water. Although a pH of about 0 in the lower cloud layer may seem extreme, Schleper *et al.* (1996) isolated microorganisms on Earth that thrive at this pH level. With regard to the high amount of UV radiation in the venusian atmosphere, cycloocta sulfur (S₈) could be used by microbes for protection (Schulze-Makuch *et al.*, 2004b). S₈ has the capability of shielding organic macromolecules, such as DNA and protein, at wavelengths most susceptible to UV damage. S₈ is also thermodynamically stable and does not react with sulfuric acid. In their attempt to identify the unknown UV-absorber in the venusian atmosphere (Fig. 1), Hapke and Nelson (1975) concluded that S₈ along with some polymorphic sulfur provided the best match. If S₈ can be used as a kind of “sunscreen,” it would explain why only minute amounts of organic compounds were detected by spectral methods (*e.g.*, Plummer, 1969). A somewhat analogous process is observed on Earth, where some purple sulfur bacteria, green sulfur bacteria, and

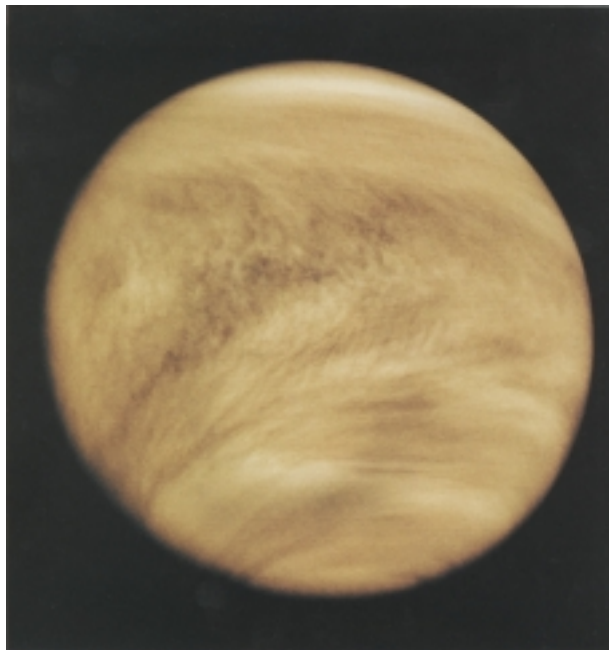
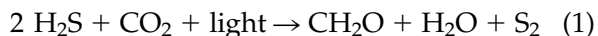


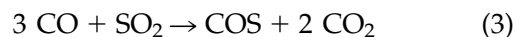
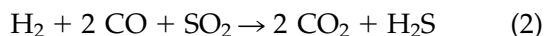
FIG. 1. Venus as it appears in reflected UV light. The dark areas on the image are caused by the UV absorber, which likely consists of various allotropes of sulfur. Source: NSSDC (http://nssdc.gsfc.nasa.gov/photo_gallery/photogallery-venus.html).

some cyanobacterial species deposit elemental sulfur granules outside of the cell (*e.g.*, Pierson *et al.*, 1993; Tortora *et al.*, 2001). Recent investigations of thermophilic microbes in Yellowstone National Park, Wyoming, revealed microbial filaments covered entirely by a mineral phase that contains significant amounts of elemental sulfur (T.R. McDermott, personal communication, 2005).

Schulze-Makuch and Irwin (2002) suggested the possibility of phototrophic life at Venus based on Photosystem I. Anoxygenic photosynthesis commonly occurs in anaerobic near-surface environments on modern Earth. Many organisms using this photosystem thrive in warm seas, soils, and hot springs (*e.g.*, Vethanayagam, 1991; Bryantseva *et al.*, 2000) on Earth, and may have been ideal inhabitants for a warm proto-ocean on early Venus:



Alternatively, Schulze-Makuch and Irwin (2002) suggested possible metabolic pathways for chemotrophic organisms that would be reasonable under environmental conditions prevailing in the current venusian atmosphere:



The Gibbs free energy yielded would be larger than 240 kJ/mol for either Pathway 2 or 3. The presence of both types of organisms would allow energy cycling: the organisms using Photosystem I would produce water, elemental sulfur (usable for UV protection), and reduced organic carbon, while the chemotrophic organisms would oxidize carbon and produce reduced sulfur compounds, which, in turn, could be used by the phototrophic organisms to start their metabolic reactions. Thus, the presence of microbial life in the current venusian atmosphere has to be considered as a distinct possibility.

Origin of life in an atmosphere is generally considered to be unlikely (*e.g.*, Schulze-Makuch and Irwin, 2004), though it cannot be dismissed *a priori*. In the case of Venus, additional possibilities are reasonable, both of an ancient origin in an early ocean and of the transport of microbes from Earth or Mars. As Venus' geologic evolution has likely deleted any possible paleontological register of ancient life on the surface, the presence of

microorganisms thriving in the atmosphere is the only testing bench for the putative biological history of the planet. All these arguments highlight the necessity of considering a survey of Venus as a main objective in the astrobiological exploration of the Solar System. The Venus Express Mission, launched in November 2005, will contribute to an improved understanding of the chemistry, dynamics, and radiative balance of the lower atmosphere, and may reveal localized volcanic activity. The abundance measurements of H₂O, SO₂, COS, CO, HCl, and HF, and their horizontal and vertical variation, especially for H₂O, are especially relevant to the feasibility of life in the venusian atmosphere.

Mars

Life on the surface of Mars appears to be unlikely because of (1) the thin atmosphere that allows harmful UV radiation to reach the surface, (2) the lack of liquid water and the desiccating conditions on its surface, (3) a lack of magnetospheric shielding, and (4) oxidized soil chemistry. The atmosphere is extremely cold and thin, and provides only a minor amount of shelter for living organisms. Equally, it is difficult to preserve organic matter or geochemical evidence of biological activity in the present-day surface environment (McDonald *et al.*, 1998; Benner *et al.*, 2000; Komatsu and Ori, 2000). The atmosphere itself as a microbial habitat is even more implausible, because environmental constraints are much more severe than on the surface of Mars.

There is compelling geological, topographical, geophysical, geochemical, geomorphological, and paleohydrological evidence that liquid water flowed on the surface of Mars in the distant past and also fairly recently (Baker *et al.*, 1991, 2000; Scott *et al.*, 1995; Carr, 1996; Bridges and Grady, 1999; Malin and Edgett, 2000, 2003; Cabrol and Grin, 2001; Baker, 2001; Dohm *et al.*, 2001a,b; Ferris *et al.*, 2002; Fairén *et al.*, 2003; Squyres, 2004). In addition, the D/H ratio of the atmosphere attests that Mars has lost water to space over time (Yung *et al.*, 1988; Donahue, 1995), perhaps as much as 75% of its original reservoir (Jakosky and Phillips, 2001). Much of this water loss may have occurred rapidly early in martian history because of impact erosion and hydrodynamic escape (Melosh and Vickery, 1989; Chassefiere, 1997a; Lammer *et al.*, 2003), though there is evidence for (periodic) oceans later in martian history (*e.g.*,

Fairén *et al.*, 2003). The Noachian oceans, and possibly any subsequent liquid water-mass on Mars, were enriched in iron hydroxides and magnesium sulfate salts, as revealed by the Mars Exploration Rover Opportunity after analyses on the sediments deposited at Meridiani Planum (Öner *et al.*, 2004). The CO₂, SO₂, and water generated from volcanism and flood outbursts would have produced the acidic conditions necessary to generate extensive sulfate salt emplacement while inhibiting carbonates from forming on the martian surface (Fairén *et al.*, 2004a–c). Even today, liquid water can exist transiently in rock pores near the surface when ice is melted by the Sun. Brines can even exist longer at temperatures below the freezing point of water.

If liquid water flowed on the surface of Mars, temperatures compatible with the perseverance of life must be assumed. All theories for the origin of life appear to be compatible with conditions on Mars during its early history (Davis and McKay, 1996). Therefore the origin of life on Mars is clearly plausible (*e.g.*, Irwin and Schulze-Makuch, 2001), especially during the Early to Middle Noachian, when conditions are hypothesized to be quite similar to those on Earth (Baker *et al.*, 2002a,b). Thus, life could have existed on the surface of Mars, but current surface conditions are not suitable for life. Any organism would have had to retreat to an ecological niche, most likely into the subsurface (Farmer and DesMarais, 1999; Hofmann and Farmer, 2000). Alternatively, microbial life could have survived in a dormant form (such as a spore state) on the martian surface only to become active if environmental conditions such as periodic flooding would allow (Irwin and Schulze-Makuch, 2004; Schulze-Makuch *et al.*, 2005).

The occurrence of persisting periods of extremely cold and dry conditions during the Hesperian and Amazonian Periods, punctuated by transient Tharsis-induced flooding and associated inundations and milder conditions (*e.g.*, Baker *et al.*, 1991; Fairén *et al.*, 2003), raises many questions about life's adaptation and survival. In fact, the martian substrate could have maintained large amounts of H₂O between dry periods, including liquid water in some locations (Barlow *et al.*, 2001), especially where elevated geotherms have persisted, such as in parts of the Tharsis and Elysium regions (Dohm, 2005). If these locations are similar to magmatic/aqueous environments on Earth, then an enormous amount of biologic activity may

occur between 0.5 and 1 km depth. Early estimates indicate that up to 10% of the Earth's biosphere lies more than 0.5 km beneath the surface (Parkes *et al.*, 2000). Mars likely contains liquid water in the subsurface in various locations that may be connected to regional deep-seated aquifers and widely dispersed locally perched aquifers, especially where there may be elevated heat flow. These subsurface water bodies may be separated by extensive and thick cryosphere regions.

As water became increasingly internalized during the martian history, so too may have any existing biota (Boston *et al.*, 1992). Life could have retreated to the deep subsurface under the permafrost and continued to thrive as microbes do on Earth, in deep granitic and basalt aquifers (Olson *et al.*, 1981; Pedersen and Ekendahl, 1990; Stevens and McKinley, 1995; Chapelle *et al.*, 2002). While the putative plate tectonic activity (Sleep, 1994) of early martian history ceased (Connerney *et al.*, 1999; Baker *et al.*, 2002a,b; Fairén *et al.*, 2002), volcanism and tectonism have continued on Mars until geologically recent time, and may still be active (Anderson *et al.*, 2001a; Dohm *et al.*, 2001a; Hartmann *et al.*, 2003; Mitchell and Wilson, 2003; Ferrill *et al.*, 2004; Márquez *et al.*, 2004; Wyrick *et al.*, 2004). Subsurface geothermal areas may thus provide a suitable habitat for chemoautotrophic organisms that sustain themselves by oxidizing free hydrogen to water provided by volcanic outgassing or serpentinization reactions in the martian crust (Sleep *et al.*, 2004).

Radiation sources beneath the surface could also split molecular water into hydrogen and oxygen, the former of which could be used as a basic energy source for microbial metabolism. Subsurface hydrothermal convective plumes (Travis, 2003) may also provide a sequence of temperatures that serve as a refuge for a wide variety of microorganisms with specific thermal requirements. The convective patterns inside plumes are stable and long-lasting, and thus could provide a source of nutrients for microbial communities living within a hydrothermal convection system. For example, the episodically active Tharsis magmatic complex (Anderson *et al.*, 2001b; Dohm *et al.*, 2001a), recently referred to as a superplume (Baker *et al.*, 2002a,b), is the dominant heat release of the planet's internal heat energy. Tharsis has provided extremely long-lived environments where magma has mixed with water to trigger floods of enormous magnitudes (Dohm *et al.*, 2001b). This persistent heat engine, which has

been active for more than approximately 3.6 Ga, along with the possible vast subterranean voids in the martian crust (Boston *et al.*, 1992; Rodriguez *et al.*, 2005a,b) hypothesized to exist in the Tharsis and surrounding regions, gives rise to the distinct possibility that life not only gained a foothold on Mars, but has also been able to persist underground to the present.

Alternatively, chemoautotrophs could reduce carbon dioxide to methane, or recycle atmospheric carbon dioxide and oxygen, which are co-deposited on the polar ice caps. Basal melting of polar deposits consisting of H₂O and other constituents (Byrne and Ingersoll, 2003; Titus *et al.*, 2003) would allow water to carry these constituents, including oxygen in dissolved form, toward the deeper zones of the groundwater flow system, where thermodynamically favorable oxidation reactions could sustain a limited, but relatively stable, subsurface microbial ecosystem.

Putative ancient drainage basins, which may have resulted in long-lived aquifers of regional extent, could have provided microbial communities with nutrients. Examples include a Europe-sized basin/aquifer system, which has been proposed to have sourced the circum-Chryse and northwestern slope valleys outflow channel systems, the northeast and northwest watersheds of Tharsis, respectively (Dohm *et al.*, 2001a), and the Arabia Terra impact basin/aquifer system in the eastern equatorial region (Dohm *et al.*, 2004a). Groundwater flow would largely be confined to the basement bedrock and rock/sediment beneath the overlying permafrost layer, occasionally percolating to the surface where fractures in the permafrost layer would provide a suitable conduit after a certain pressure threshold is overcome. Physical evidence for past, sometimes massive, eruptions from the subsurface, especially in the older highland regions, is abundant (Scott and Tanaka, 1986; Baker *et al.*, 1991; Crown *et al.*, 1991; Boston *et al.*, 1992; Scott *et al.*, 1995; Dohm *et al.*, 2001a,b).

Methanogenesis is a common and presumably ancient metabolic pathway for microbial life on Earth, which may also be used by putative life on Mars. Terrestrial anaerobic methanogens utilize H₂ and CO in metabolism, and release CH₄ as a by-product. Conversely, multiple terrestrial archaeal groups that live in anoxic cold seep marine sediments oxidize the methane buried beneath the seafloor to CO₂, thus consuming up to 20% of the total methane flux to the atmosphere (Orphan *et al.*, 2002). Methane hydrates are un-

stable on the surface of Mars under current ambient pressure/temperature conditions, but stable in the subsurface at depths greater than 15 m [>140 kPa (Max and Clifford, 2000)], which suggests that methane on Mars may reside beneath the cryosphere. The recent discovery of methane in the martian atmosphere (*e.g.*, Formisano *et al.*, 2004) may point toward life activity among other alternatives such as volcanic activity or geochemical reactions.

Life could also exist in the fringe areas of the polar ice caps of Mars (Córdoba-Jabonero *et al.*, 2005). Solar energy sources have been continuously available until the present. Analogue environments on Earth are the Antarctic dry valleys and “cool” hydrothermal systems that exist in the Arctic and Antarctic. Cryptoendolithic cyanobacteria live in arid landscapes 0.5–5 mm below the rock surface because of their need for UV shielding from the hostile environment, yet they are still able to carry out photosynthesis and meet their liquid water and nutrient needs (Friedmann, 1980, 1982; Friedmann *et al.*, 1980, 1993; Friedmann and Weed, 1987; Nienow *et al.*, 1988; Vestal, 1988).

Impact-induced porosity should be common on Mars (*e.g.*, Rodriguez *et al.*, 2005b) and may have provided shelter for putative microbial organisms (Cockell and Barlow, 2002). There is also direct evidence of vast subterranean voids in the crust of Mars, which include lava tube caves (Fig. 2) (Boston, 2004) and collapse features such as chaotic terrains, pit crater chains, and vast canyon systems, as seen in Valles Marineris and surrounding regions (Lucchitta *et al.*, 1992; Dohm *et al.*, 2001a; Komatsu *et al.*, 2004; Rodriguez *et al.*, 2005a,b; Wyrick *et al.*, 2004). Chaotic terrain, for example, is observed at the headwater regions of the circum-Chryse outflow channels. These putative cavernous systems are believed to be much larger than their equivalents on Earth because of Mars’ lower gravity (0.38 G), which allows larger spans of unsupported rock to exist. Permafrost caves caused by ground suffosion may also exist on Mars. Caves, subsurface fissures, microcracks, and intergrain pore spaces would shelter microbial life from UV radiation, desiccation, temperature fluctuations, and other weather-related phenomena. The subsurface in general, and caves in particular, thus may provide a suitable habitat or at least shelter for life on Mars (Fig. 2). We emphasize that exploration of the subsurface of Mars

should be a main objective in the exploration of the Solar System.

Ices on Mercury and the Moon

Mercury’s conditions are extremely harsh. The planet is closer to the Sun, and thus during its embryonic stage of formation probably received smaller amounts of volatile compounds than the rest of the terrestrial planets. Near its poles, frozen water ice has been discovered within permanently shadowed impact craters (Fig. 3) (Harmon and Slade, 1992; Ingersoll *et al.*, 1992; Paige *et al.*, 1992; Slade, 1992; Slade *et al.*, 1992; Harmon *et al.*, 1994, 2001), where volatiles that include water are stable for long periods of time at temperatures of about 112 K. The area covered by the ice deposits is estimated to be about 10,000 km² (Slade *et al.*, 1992). Though the ice probably originated from relatively recent comet or water-rich asteroid impacts, it is possible that the remnant waters could archive early solar system information if the impacts and partial water infilling occurred relatively early in the development of the planet (*e.g.*, shortly after the formation and hardening of the crust).

Considering the latter case, water ice on Mercury may hold some clues with regard to the materials that protected and catalyzed the first biological synthesis on Earth. Irwin and Schulze-Makuch (2001) assigned Mercury a Plausibility of Life (POL) rating of IV (low), which is based on the assessment that there is a reasonable inference of past conditions suitable for the origin of life prior to the development of conditions so harsh as to make its perseverance at present conceivable only in isolated habitats, such as beneath polar ice deposits. The high temperatures on Mercury, however, and its probable formation in a region of the Solar System where water is mostly unstable suggest that this planet formed under anhydrous conditions, so that the chance for life having emerged on Mercury is very low. Thus, a POL rating of V may be more appropriate.

Because of its mode of origin, the Moon is extremely anhydrous. Given that no water or other volatiles ever formed an atmosphere or were present on the surface or in the subsurface, the Moon is not a likely candidate for the origin or persistence of life. However, the Moon may hold some evidence of the early evolution of life on Earth, since meteorite impacts on Earth may have delivered biogenic material to the surface of the

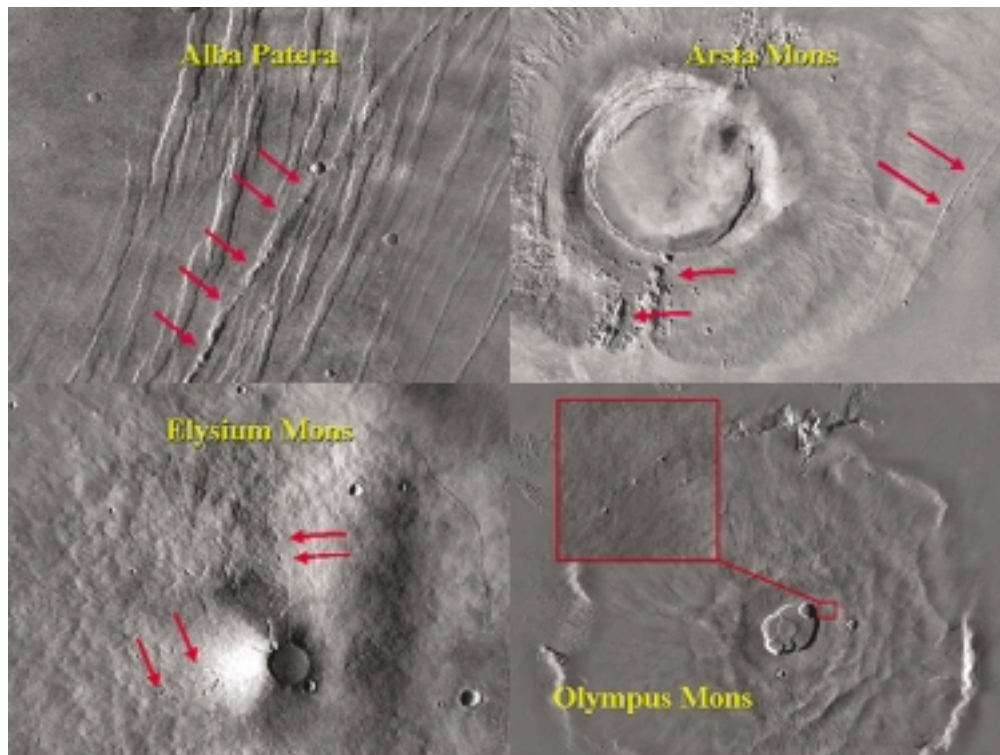


FIG. 2. Collapsed lava tubes on Mars highlighted by arrows (composite image provided by R.D. "Gus" Frederick, Silverton, OR, based on imaging data from NASA).

Moon (Armstrong *et al.*, 2002). The ice at the south pole of the Moon may also serve as a relatively accessible reservoir to analyze cometary ice and provide water for possible future human habitation of the Moon. However, the ice would have to be extracted from the subsurface as the surface ice has been altered by radiation. About 2–3 m of lunar soil cover is required to protect surface ice from radiation damage.

INCENTIVES FOR ASTROBIOLOGICAL EXPLORATION OF THE INNER SOLAR SYSTEM

With regard to the inner planets of the Solar System, Mercury and the Moon have the lowest potential for life because they have no significant atmosphere, probably no liquid water, and exhibit extreme temperature variations between the sun-lit side and the shadow side. However, ice samples on Mercury and the Moon may contain information about pre-biogenic and possible biogenic material from Earth (and elsewhere), which warrants further exploration.

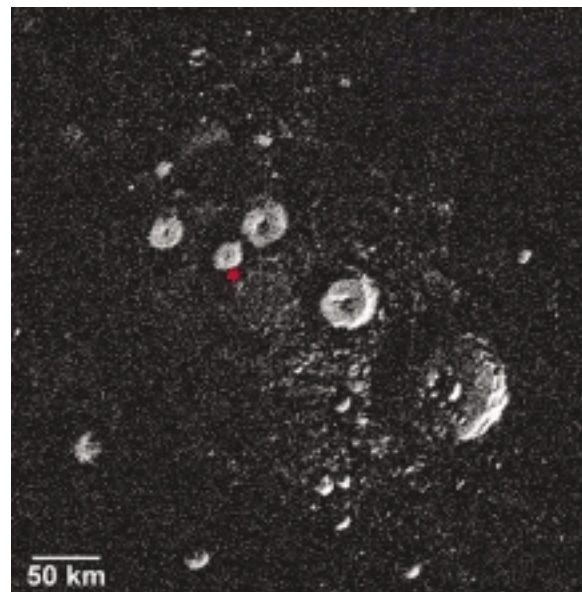


FIG. 3. Radar image of craters in the north pole of Mercury. The radar signature of ice is denoted in the crater's bright floors. The red spot marks the North Pole position. This image was captured on July 25–26, 1999, with the Arecibo radiotelescope.

Mars and Venus are possible locations for extraterrestrial life. Conditions on both Venus and Mars were such, in the early Solar System, that they may have facilitated life on their surfaces and/or surface oceans. Today, however, this is no longer the case. Surface conditions on Venus are hot and desiccating, and on Mars conditions are oxidizing and desiccating with high fluxes of UV radiation. However, if life evolved independently on either or both of these planetary bodies early in Solar System history, because of an independent genesis or via transport from Earth or another inner planet by meteorite impact [*e.g.*, impact panspermia (Melosh, 1988); also supported by recent photo-reversion studies under space conditions (*e.g.*, Fekete *et al.*, 2004; Rontó *et al.*, 2004)], then life could have persisted on Venus and Mars. Subsequent climatic and geological changes, however, may have driven any organisms into refugia such as the venusian atmosphere and martian subsurface. The question arises, then, as to whether those organisms could have adapted to the extreme environmental changes that occurred with time? Would directional selection have driven putative ancient life on the surface of Venus and Mars to find safe havens? Were the environmental changes gradual enough for life to adapt by natural selection? The environmental changes on Venus and Mars were certainly extreme, judging by current conditions. Microbes on Earth, however, are known to be capable of adapting to very extreme changes, and it is likely that similar organisms on Venus and Mars may have employed similar adaptation mechanisms. In the case of Mars, withdrawal into a subsurface niche might have been easier because of the more protective nature of subsurface environments. In the case of Venus, the atmosphere, though it would have provided less protection than a subsurface environment, would have had to offer plentiful and continuous energy sources. Most of the subsurface life on Earth, below a shallow soil horizon, is unicellular, and permanent life in Earth's atmosphere (*e.g.*, Sat-

ler *et al.*, 2001), if it can be confirmed, is unicellular as well. Thus, the most optimistic expectation for finding life in the inner Solar System would be in the form of unicellular life (Table 1).

PROPOSED ADVANCES IN PLANETARY EXPLORATION STRATEGIES

Prior (robotic) missions to planetary bodies such as Mars have focused either on exploration of a single site with a single lander (immobile agent) or rover (mobile agent) or on a global mapping orbiter. The lander/rover missions tend to analyze a rather confined, readily accessible site in more detail, but often at the expense of a regional understanding, while orbiter missions return immense data sets that tend to overlook the local and regional significance.

Atmospheric and surface conditions of the inner planets Mercury, Venus, Earth, and Mars challenge spacecraft landing operations and exploration. Current surface exploration scenarios favor single lander/rover missions at the expense of mission redundancy, mission safety, and mission science return. Single landers/rovers are also restricted to small areas of exploration and are not likely to explore potentially hazardous, but scientifically interesting, terrains, which include: (1) canyons (*e.g.*, Valles Marineris on Mars), (2) mountain ranges (*e.g.*, Thaumasia highlands on Mars, Isthara Terra on Venus), (3) sites of suspected magmatic-driven uplift and associated tectonism and possible hydrothermal activity (*e.g.*, plume-related activity such as hypothesized for the central part of Valles Marineris and the Warrego Valles rise on Mars, and Maxwell Montes on Venus), (4) polar ice caps (*e.g.*, Mars), (5) ice deposits within impact basins (*e.g.*, Mercury and Moon), (6) volcanoes of diverse sizes and shapes (*e.g.*, Venus and Mars), (7) putative ancient accreted terrains and associated volcanism (*e.g.*, Mars), (8) regions indicating potential recent hydrologic activity such as spring-fed seeps (*e.g.*, Mars), and (9) chaotic terrain (*e.g.*, source areas of the circum-Chryse outflow channel system on Mars). Ironically, all of the terrains listed above are particularly crucial for astrobiological-oriented exploration. As such, a change in how we approach future planetary exploration is overdue and required; in place of single orbiter, lander, or rover missions, a multi-tier (*e.g.*, orbit-atmosphere-ground/subsurface), multi-agent (*e.g.*,

TABLE 1. PRINCIPAL REFUGIA FOR LIFE ON VENUS, EARTH, AND MARS

<i>Refugium</i>	<i>Venus</i>	<i>Earth</i>	<i>Mars</i>
Atmosphere	Possible	Possible	No
Surface	No	Yes	Unlikely
Subsurface	Unlikely	Yes	Possible

orbiters, blimps, and rovers/landers/sensors) hierarchical mission architecture with varying degrees of mission operation automation/autonomy is proposed (Fink *et al.*, 2005a–c). This novel mission architecture will not only introduce, for the first time, redundancy and safety into missions, but also enable distributed scientific exploration, spanning larger surface areas than previously possible.

Several example scenarios are outlined in the following (for further detail see Fink *et al.*, 2005c):

- *Planets with atmospheres and non-extreme surface temperatures* (e.g., Mars). Orbiter-guided deployment of airborne (blimp/balloon) units, which in turn deploy and communicate with mobile and immobile ground-based agents to prime locations on the surface, would allow for optimal investigation of such planetary bodies. An example of mobile ground-based agents would be expendable rover units. An example of an immobile ground-based agent would be the relatively inexpensive Beagle 2 lander. Multi-tiered exploration system architectures can be specifically tailored to allow for investigations into locations that are too risky for conventional mission deployments but are of great scientific interest. To ensure successful science data retrieval, orbiters could, at first, deploy airborne and ground-based “scouts” (*i.e.*, special purpose sensors) to relay pre-major-deployment information with regard to, for example, terrain hazards and atmospheric conditions. If, for example, the “scouts” record (a) ample conditions in an operational area (e.g., low wind) or (b) an interesting feature such as a unique rock and/or rock outcrop, a giant landslide that initiates from the walls of, for example, Valles Marineris, a water seep, or a region of discernible elevated heat flow, a major deployment would then occur. In the case of the Northwestern Slope Valley’s region (Dohm *et al.*, 2004b), a multi-tier exploration system could hone in on the expected diversity in rock lithology, in part, exposed by tectonism and eolian and fluvial erosion. More specifically, orbiter-guided airborne units such as blimps would be able to descend into this region and hone in on features of special interest (see Appendix for details).
- *Planets with atmospheres and extreme surface temperatures* (e.g., Venus). Orbiter-guided deployment of balloon/blimp units, in such conditions,

would have the capability to investigate larger surface areas in greater detail from above than has previously been done. If surface temperatures allow, deployment and communication would be achieved with temperature-resistant immobile sensor webs (for atmospheric sampling, see below under Application to atmospheric exploration).

- *Planets without atmospheres and extreme surface conditions* (e.g., Mercury, Moon). Orbiter-guided deployment of ground-based mobile rover units and immobile sensor webs would allow for comprehensive and detailed exploration of these kinds of planetary surfaces.

A multi-tier, hierarchical mission architecture would overcome the inherent challenge of geologic planetary surface exploration: airborne units (orbiters in conjunction with balloons/blimps) possess overhead perspectives at different length scales/resolutions, which could provide guidance to ground-based agents (e.g., mobile rover units). For example, one of the airborne units could detect a scientifically interesting feature or a hazard or obstacle hidden from a rover camera by an intervening mountain. Such an airborne unit would acquire terrain images that could subsequently be processed by automated feature-extraction software packages, such as the Automated Geologic Field Analyzer (AGFA) (Fink *et al.*, 2005d). The feature data would be used by science prioritization algorithms to choose potential targets for close examination by the rovers and for determining safe passages to their designated targets. At the respective targets, the rovers would conduct *in situ* science experiments and thereby gather data that complement the remote sensing data, obtained by the airborne units. In addition, such a system could help direct rovers equipped with a driller or immobile drill rigs to localities of elevated heat flow and near-surface groundwater to explore the near-subsurface and collect samples to be returned to the International Space Station or Earth for analysis.

Application to sample return missions

In our view, the highest priority for a sample return mission should be a potential hydrothermal site on Mars (e.g., Dohm *et al.*, 2004b; Schulze-Makuch *et al.*, 2004a). The Northwestern Slope Valley region, for example, is a prime candidate site for such future science-driven Mars explora-

tion because it records Noachian to Amazonian Tharsis development in a region that encapsulates (1) a diverse and temporally extensive stratigraphic record, (2) at least three distinct paleohydrologic regimes, (3) gargantuan structurally controlled flood valleys that generally correspond with gravity and magnetic anomalies, possibly marking ancient magnetized rock materials exposed by fluvial activity, (4) water enrichment, as indicated by Mars Odyssey and impact crater analyses, (5) long-lived magma and groundwater/ice interactions that could be favorable for the development and sustenance of life, and (6) potential paleosol development (Dohm *et al.*, 2004b). As such, there is a high probability that this region could yield significant geologic, climatic, and astrobiological information that would revolutionize our understanding of Mars. Interestingly, this region also indicates elevated chlorine (*e.g.*, Boynton *et al.*, 2004) and methane (*e.g.*, Formisano *et al.*, 2004) abundances. Among several possible explanations (J.M. Keller *et al.*, manuscript in preparation, 2005), the Odyssey Gamma Ray Spectrometer (GRS)-based elevated chlorine signature could indicate aqueous processes in the past or present, which includes magma–water interactions (Dohm *et al.*, 2004b, 2005; Dohm, 2005). Another region where water may be present at or near the surface is within Valles Marineris because of its geomorphic expression (*e.g.*, Komatsu *et al.*, 2004), which includes dendritic valleys (Magnold *et al.*, 2004) and relatively low topography. At a site difficult to access, such as inside Valles Marineris, sample return missions are feasible using a novel mission architecture (Fink *et al.*, 2005a–c).

Application to atmospheric exploration

For all three terrestrial planets with an atmosphere, it is crucially important to know how the atmospheres of the planets changed over time. Did all three planets start out with the same type of atmosphere? Was liquid water stable on the surface of all three planets early after the Solar System formed? Did Mars have sufficient atmosphere for life to thrive at its surface, such as during the transient magmatic-driven hydrologic/climatologic events?

To answer these questions, we have to understand the amount and composition of the pristine volatiles with which the terrestrial planets were seeded (Fairén, 2004) and sample some of the

cometary material that has been preserved through time. Thus, sample analysis and sample return missions, such as the Stardust mission encounter with comet WILD-2, are consistent with these goals. The water-enriched material could provide critical clues with regard to the nature of the molecules that protected and catalyzed the synthesis of the first biological structures on Earth, and possibly on Mars and Venus. Understanding the evolution of atmospheres through time will provide us with answers as to why Venus turned into a “hot house,” Mars into a “cold house,” and Earth into a planet just right to allow for stable oceans on its surface throughout much of the history of the Solar System.

We know now that these changes were not only due to the position of the planets around the Sun, but to many factors, including the dynamics of the early atmospheres, environmental interactions between the atmosphere and surface/subsurface, meteorite impacts, orbital parameters such as tilt of the axis, inner structuring and differentiation, thermal properties of the crust, volcanic degassing rates, etc. An understanding of these interactions will enable us to predict future climate changes on Earth and the other terrestrial planets, and assess their potential habitability for a wide range of life forms (*e.g.*, from microbes to humans). The Venus Express Mission is consistent with those objectives, but we should move more boldly, such as launching a sample return mission to the venusian atmosphere.

Evidence has recently been presented that the atmosphere of a planet may also serve as a primary habitat for microbial life (Dimmick *et al.*, 1979; Sattler *et al.*, 2001) as discussed before. These findings and the more benign conditions in the venusian atmosphere, compared with Earth’s atmosphere, have led several authors to speculate on the possibility of microbial life in the venusian atmosphere (*e.g.*, Sagan, 1961; Grinspoon, 1997; Schulze-Makuch and Irwin, 2002, 2004; Schulze-Makuch *et al.*, 2004b). The atmosphere of Earth serves as a transient habitat for microbes and even macroscopic life, and experiments should be conducted to test whether it also serves as a permanent habitat for microbial life in spite of harsh conditions. Compared with the atmosphere of Earth, the atmospheric conditions on Venus are much more benign with respect to temperature, pressure, and particle residence times, and thus microbial life in the venusian atmosphere is a distinct possibility. Therefore, a sample return mis-

sion to the venusian lower cloud layer, where microbes may reside, should be considered. Schulze-Makuch *et al.* (2002b) contemplated various mission options and concluded that a sample return mission involving a Parachute Drop–Balloon Floation Mission, designed to return astrobiologically relevant material for analysis to the International Space Station, would be the most preferable option. Even if the promising mode 3 particles in the venusian atmosphere were not of biological nature, a sample return mission would significantly increase our knowledge about the composition and dynamics of the atmosphere.

The relative ease of reaching Venus and returning to Earth and the availability of appropriate existing technology make such a mission feasible in the short term. For example, for a Venus net sample return mass of 100 g at an altitude of 51 km, a blimp/balloon would need to be deployed with a radius >0.4 m (see Appendix for details). The blimp/balloon would have the capability of hovering at the altitude of 51 km or descending to lower altitudes, where it could collect samples of cloud particles with aerogels similar to STARDUST and GENESIS [*e.g.*, Knollenberg and Hunten (1980) reported a cloud particle density of 10–100 particles/cm³ at about 50 km altitude]. These cloud particles, once obtained by the blimp/balloon, could be transported into orbit, and from there to the International Space Station or Earth for analysis. Thus, technology for a sample return mission to Venus exists, and the mission could be done in short order.

CONCLUSIONS

Venus, Earth, and Mars may have had liquid water bodies on their surfaces early in the Solar System history. Any liquid water on the venusian surface evaporated, but significant amounts of water remain in the atmosphere. On Earth, of course, liquid water is abundant and stable at the surface, as well as in the subsurface and the atmosphere. Because of the thin martian atmosphere, liquid water in most locations is not stable at the surface of Mars. Large liquid and frozen water reservoirs, however, are likely to exist in the martian subsurface. The search for life on the inner terrestrial planets should follow the presence of water (both liquid and solid). Life is present in the subsurface of Earth, on its surface, and, at least transiently, in its atmosphere. It may be present in the venusian

atmosphere and the martian subsurface (Table 1). Missions should be designed to explore these potential habitats. In addition, ices on Mercury and the Moon should be explored for remnant biogenic material from the early evolution of life on Earth (and elsewhere). Especially desirable are sample return missions and missions that include a hierarchical architecture with varying degrees of mission operation autonomy, which will allow optimal reconnaissance of planetary environments.

APPENDIX

1. Assumptions for the calculations for the proposed missions to Mars and Venus

The calculations are based on the following parameters for Mars provided by NASA's Goddard Space Flight Center (<http://nssdc.gsfc.nasa.gov/planetary/planetfact.html>):

- Surface atmospheric temperature: 210 K
- Surface atmospheric pressure: 636 kg/ms² (*i.e.*, Pa)
- Molecular weight, atmosphere: 0.04334 kg/mol
- Molecular weight, balloon gas: 0.004 kg/mol (He)
- Skin surface density for 12.7- μ m-thick Mylar film (balloon skin): 0.0187 kg/m² (J.L. Hall, personal communication, 2004)

The calculations are based on the following parameters for Venus provided by Marov and Grinspoon (1998):

- Atmospheric temperature at 51 km: 342 K
- Atmospheric pressure at 51 km: 93,470 kg/ms² (*i.e.*, Pa)
- Molecular weight, atmosphere at 51 km: 0.04368 kg/mol (98% CO₂, 2% N₂)
- Molecular weight, balloon gas: 0.004 kg/mol (He)
- Skin surface density for 12.7- μ m-thick Mylar film (balloon skin): 0.0187 kg/m² (J.L. Hall, personal communication, 2004)

2. Assumptions for the mathematical derivation of the balloon-lift-equation for planetary bodies with atmospheres

- Ideal gas equation holds approximately true
- Barometric pressure formula holds approximately true

- Pressure difference between top and bottom of the balloon negligible
- Pressure inside balloon equals ambient pressure outside balloon (*i.e.*, no super-pressure balloon)

3. Mathematical derivation of the balloon-lift-equation for planetary bodies with atmospheres

$M_{\text{atmosphere}}$ = mass of atmosphere replaced by balloon

M_{balloon} = mass of balloon (skin) including floating gas

M_{payload} = useful payload (gas tank, sensors, and instruments)

Note that the gas-tank to gas (He) mass-ratio is commonly assumed to be around 5:1 (J.L. Hall, personal communication, 2004).

$$M_{\text{atmosphere}} = M_{\text{balloon}} + M_{\text{payload}}$$

$$\Rightarrow \frac{4}{3} \pi r^3 \rho_{\text{atmosphere}} = 4\pi r^2 \rho_{\text{skin}}$$

$$+ \frac{4}{3} \pi r^3 \rho_{\text{gas}} + M_{\text{payload}}$$

$$\Rightarrow \frac{4}{3} \pi r^3 \frac{M_{\text{atmosphere}} P}{RT} = 4\pi r^2 \rho_{\text{skin}}$$

$$+ \frac{4}{3} \pi r^3 \frac{M_{\text{gas}} P}{RT} + M_{\text{payload}}$$

with

$$PV = nRT$$

$$\Rightarrow \frac{n}{V} = \frac{P}{RT}$$

$$\Rightarrow \frac{nM}{V} = \rho = \frac{PM}{RT}$$

$$\Rightarrow \frac{4}{3} \pi \left[\frac{M_{\text{atmosphere}} - M_{\text{gas}}}{R} \right] \frac{P}{T} r^3$$

$$- 4\pi \rho_{\text{skin}} r^2 = M_{\text{payload}}$$

This equation allows calculating the useful payload M_{payload} for a given balloon radius r if the atmospheric pressure P , the atmospheric temperature T , and the molar mass $M_{\text{atmosphere}}$ of the atmosphere at a desired balloon operation altitude h (implicitly included in atmospheric pressure P) are known in addition to the molar mass M_{gas} of the balloon gas and the skin surface density ρ_{skin} of the balloon at a known thickness. R is the universal gas constant.

In cases where the atmospheric pressure P at the desired balloon operation altitude h is not known, the pressure can be approximated by employing the barometric pressure formula as follows:

$$P = P_0 e^{-\frac{M_{\text{atmosphere}} g h}{RT}}$$

$$\Rightarrow \frac{4}{3} \pi \left[\frac{M_{\text{atmosphere}} - M_{\text{gas}}}{R} \right] \frac{P_0 e^{-\frac{M_{\text{atmosphere}} g h}{RT}}}{T} r^3 - 4\pi \rho_{\text{skin}} r^2 = M_{\text{payload}}$$

In this case the surface atmospheric pressure P_0 and the gravitational acceleration g for the planetary body have to be known, too.

In both cases either the useful payload M_{payload} can be directly calculated for a given balloon radius r , or, the necessary minimal balloon radius r can be calculated for a given useful payload M_{payload} via, *e.g.*, the ‘‘Golden-Section-Search’’ algorithm (*e.g.*, Press *et al.*, 1991) by numerically solving the cubic equation for r .

4. Application examples

Applying the above assumptions and derivations we obtain:

- For a Mars net sample return mass of 100 g at an altitude of 0 m, a blimp/balloon would need to be deployed with a radius >8 m (this includes the gas tank mass; without the tank this blimp/balloon would have a net liftable payload mass of 15.8 kg).
- For a Venus net sample return mass of 100 g at an altitude of 51 km, a blimp/balloon would need to be deployed with a radius >0.4 m (this includes the gas tank mass; without the tank this blimp/balloon would have a net liftable payload mass of 0.31 kg).

ACKNOWLEDGMENTS

We thank Chris McKay, Norm Sleep, and an anonymous reviewer for their constructive comments on this paper.

ABBREVIATION

POL, Plausibility of Life.

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