Astrobiology and Venus Exploration

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For hundreds of years prior to the space age, Venus was considered among the most likely homes for extraterrestrial life. Since planetary exploration began, Venus has not been considered a promising target for Astrobiological exploration. However, Venus should be central to such an exploration program for several reasons. At present Venus is the only other Earth-sized terrestrial planet that we know of, and certainly the only one we will have the opportunity to explore in the foreseeable future. Understanding the divergence of Earth and Venus is central to understanding the limits of habitability in the inner regions of habitable zones around solar-type stars. Thus Venus presents us with a unique opportunity for putting the bulk properties, evolution and ongoing geochemical processes of Earth in a wider context.

Many geological and meteorological processes otherwise active only on Earth at present are currently active on Venus. Active volcanism most likely affects the climate and chemical equilibrium state of the atmosphere and surface, and maintains the global cloud cover. Further, if we think beyond the specifics of a particular chemical system required to build complexity and heredity, we can ask what general properties a planet must possess in order to be considered a possible candidate for life. The answers might include an atmosphere with signs of flagrant chemical disequilibrium and active, internally driven cycling of volatile elements between the surface, atmosphere and interior. At present, the two planets we know of which possess these characteristics are Earth and Venus.

Venus almost surely once had warm, habitable oceans. The evaporation of these oceans, and subsequent escape of hydrogen, most likely resulted in an oxygenated atmosphere. The duration of this phase is poorly understood, but during this time the terrestrial planets were not isolated. Rather, due to frequent impact transport, they represented a continuous environment for early microbial life. Life, once established in the early oceans of Venus, may have migrated to the clouds which, on present day Venus, may represent a habitable niche. Though highly acidic, this aqueous environment enjoys moderate temperatures, surroundings far from chemical equilibrium, and potentially useful radiation fluxes. Observations of unusual

chemistry in the clouds, and particle populations that are not well characterized, suggest that this environment must be explored much more fully before biology can be ruled out. A sulfur-based metabolism for cloud-based life on Venus has recently been proposed (Schulze-Makuch et al., 2004). While speculative, these arguments, along with the discovery of terrestrial extremophile organisms that point toward the plausibility of survival in the Venusian clouds, establish the credibility of astrobiological exploration of Venus. Arguments for the possible existence of life on Mars or Europa are, by convention and repetition, seen as more mainstream than arguments for life elsewhere, but their logical status is similar to plausibility arguments for life on Venus.

With the launch of COROT in 2006 and Kepler in 2008 the demographics of Earth-sized planets in our galaxy should finally become known. Future plans for a Terrestrial Planet Finder or Darwin-type space-based spectrograph should provide the capability of studying the atmospheric composition and other properties of terrestrial planets. One of the prime rationales for building such instruments is the possibility of identifying habitable planets or providing more generalized observational constraints on the habitable zones of stellar systems. Given the prevalence of CO_2 dominated atmospheres in our own solar system, it is quite likely that a large fraction of these will be Venus-like in composition and evolutionary history. We will be observing these planets at random times in their evolution. In analogy with our own solar system, it is just as likely that we will find representatives of early Venus and early Earth type planets from the first 2 billion years of their evolution as it is that we will find "mature Venus" and "mature Earth" type planets that are roughly 4.5 billion years old. Therefore, in order to be poised to use the results of these future observations of extrasolar planets to make valid, generalized inferences about the size, shape and evolution of stellar habitable zones it is vital that we obtain a much deeper understanding of the evolutionary histories and divergence of Earth and Venus.

The Mars Exploration Rover findings of evidence for aqueous conditions on early Mars have intensified interest in the possible origin and evolution of life on early Mars. Yet the evidence suggests that these deposits were formed in a highly acidic and sulfur-rich environment. During this phase, Mars may well have had sulfuric acid clouds sustained by vigorous, sulfur-rich volcanism. This suggests that a greater understanding of the chemistry of the Venusian atmosphere and clouds, and surface/atmosphere interactions, may help to characterize the environment of Mars when life may have formed there. In turn, if signs of early life are found on Mars during the upcoming decades of intensive astrobiological exploration planned for that planet, it will strengthen arguments for the plausibility of life in an early and gradually acidifying Venusian environment. Of our two neighboring planets, Venus and Mars, it is not yet known which held on to its surface oceans, and early habitable conditions, for longer.

1. INTRODUCTION: A BRIEF HISTORY OF VENUS EXOBIOLOGY

The atmosphere of Venus was discovered by Mikhail V. Lomonosov at the Saint Petersburg Observatory during a transit of the sun in 1761 (Lomonosov, 1955). From that time up until the eve of the space age, Venus was widely viewed as a planet likely to have surface conditions closely resembling those of Earth, and consequently was seen as one of the most promising locations for extraterrestrial life. For centuries astronomers have been aware of the proximity of Venus to Earth in the solar system, the obvious similarity

in bulk properties between Venus and Earth, and the cloud-filled sky. The clouds were widely interpreted before the 1970's to be condensed water, and were often held to suggest the presence of a large surface reservoir of water. The current consensus of astrobiology, that life is most likely to be found on planets with liquid water reservoirs (Pace, 2001; Irwin and Schulze-Makuch, 2001), has long been held by speculative scientists, who often believed Venus to be a likely location for life. For example, the distinguished British astrophysicist Sir Arthur Eddington, in a book published in 1928, summarized these arguments and declared that "Venus, so far as we know, would be well adapted for life similar to ours… If transplanted to Venus we might perhaps continue to live without much derangement of habit" and that Mars, by contrast, "has every appearance of being a planet long past its prime" (Eddington, 1935).

This view was first seriously contradicted by data in 1956 when Earth-based observations at 3.15 cm yielded a radio brightness temperature of 620 ± 100 K (Mayer et al., 1957). This suggested to some researchers that the surface temperature of Venus was much greater than that of Earth, but alternative interpretations involved a high-altitude, non-thermal source of radiation, preserving the possibility of moderate surface temperatures. Thus, at the inception of planetary exploration the question of whether or not Venus maintained habitable conditions at the surface was still in doubt. In a 1961 paper, Sagan (1961) summarized conflicting current views on possible environmental conditions on Venus, stating: "The state of our knowledge of Venus is amply illustrated by the fact that the Carboniferous swamp, the wind-swept desert, the planetary oil field, and the global Seltzer ocean each have their serious proponents, and those planning eventual manned expeditions to Venus must be exceedingly perplexed over whether to send along a paleobotanist, a mineralogist, a petroleum geologist, or a deep-sea diver."

This question was definitively resolved with the microwave radiometer on Mariner 2, one of the first experiments at another planet from any spacecraft, which showed a distinctive signature of limb darkening at a wavelength of 1.9 cm (Sagan 1969), demonstrating that the source was a surface much hotter than the stability range of liquid water. Sagan's hypothetical manned mission would most fruitfully include the mineralogist although, as will be discussed herein, there may yet be work for the paleobotanist.

The Mariner 2 results led to a precipitous fall from grace for Venus as a home for life in both the scientific and popular literature. A New York Times editorial in February, 1963, entitled "Venus Says No", described the Mariner 2 results as "disheartening, disillusioning", and declared that "The message from Venus may mark the beginning of the end of mankind's grand romantic dreams".

By 1971, after the Venera 7 and 8 landings, it was clear that Venus possessed a surface temperature of ≈ 735K and a surface pressure of ≈ 90 bars (Marov et al. 1973). Subsequently, the subject of life on Venus received little mention in the literature. However, Sagan and Morowitz (1967) proposed the possibility of multicellular organisms generating hydrogen and utilizing float bladders in the Venusian clouds.

More recently, the possibility of surface life in early Venusian history has received support from the prevailing view (still unsupported by definitive empirical evidence) that Venus possessed surface oceans early in its history, by accumulating evidence for a fast origin of life on the young Earth, by dynamical and microbiological support for the notion that meteorites with viable microorganisms were likely exchanged by the young terrestrial planets, and by the continuing discovery of terrestrial extremophile organisms inhabiting a wide range of physical conditions and employing a wide range of metabolic strategies.

Extensions of these same arguments, plus observations of the surprising adaptability of terrestrial life to even seemingly unlikely niches where liquid water is available in some form, has lead some authors to argue recently for the possibility that life on Venus, rather than going extinct when surface water was lost, may have migrated to the global cloud deck, and may possibly persist there today (Grinspoon, 1997; Schulze-Makuch et al, 2004).

In the last decade, exobiology, now astrobiology, has flourished as a new meta-discipline (Morrison, 2001). A major focus of this field is the effort to develop a generalized understanding of terrestrial planet evolution in order to understand the locations, demographics, morphologies, and longevity of stellar habitable zones and the types of terrestrial planets that may inhabit them. Exploration of Venus is a central and indispensable part of this effort.

2. HABITABLE CONDITIONS ON EARLY VENUS

While early planetary exploration definitively revealed that surface conditions on Venus are now incompatible with organic life, subsequent developments in both planetary science and astrobiology have supported the belief that earlier in its history Venus may have supported life.

Here we will not attempt a complete review of ideas about the formation and early evolution of Venus, but merely point out some aspects of our contemporary understanding of these topics which are most relevant to astrobiology.

The original water abundance of Venus is highly unconstrained. The high D/H ratio observed, 2.5×10^{-2} or ~150 times terrestrial (Donahue et al. 1997) has often been cited as evidence of a large primordial water endowment (Donahue et al. 1982). However, theoretical work has shown that given

the likelihood of geologically recent water sources and the large uncertainty in the modern and past hydrogen and deuterium escape fluxes, the large observed D/H may result from the history of escape and re-supply in the most recent $\sim 10^9$ years of planetary evolution, and does not reliably or uniquely preserve a signal of primordial water escape (Grinspoon 1997, 1998, 1993; Donahue, 1997).

Thus, at present the best arguments for a sizable early Venusian water endowment are those based on consideration of likely modes of planet formation and early volatile delivery, along with the constraint that Earth received at least one FTO (full terrestrial ocean) of water during formation. Indeed, most models of water delivery to early Earth involve impact processes that would have also supplied Venus with abundant water. Whether the Earth's water was primarily delivered within rocky material from the inner solar system (Morbidelli et al., 2000) or icy material from the outer solar system (Grinspoon, 1987; Ip and Fernandez, 1998), gravitational scattering of objects from these source regions would have ensured that Venus received a roughly similar amount. It is worth noting that the stochasticity of the volatile accretion process for terrestrial planets is still largely unknown. It has even been suggested that Earth may have received most of its water in one large planetesimal impact (Morbidelli et al., 2000). Stochastic processes could have created large inequities in original volatile inventory among neighboring planets. However, given the great similarity in bulk properties between Venus and Earth, their close proximity in the Solar System, and present understanding of accretional processes, the best assumption at present is that Venus and Earth started with similar water endowments.

Given the faint young sun (Kasting and Grinspoon, 1991) and the almost certain presence of liquid water oceans on the young Venus, the interest for astrobiology is obvious: According to our current understanding of the required conditions and timescale for the origin of life, Venus is a place where this should have occurred. Even if a separate origin of life did not occur on Venus (or on Earth) there is good reason to believe that interplanetary transfer by impact ejecta would have distributed life among the young terrestrial planets (Melosh, 1988).

In the scientific literature, much more attention has been given to the possibility of life on early Mars during a period in which that planet may have been substantially warmer and wetter than at present. This bias is in part due to the fact that the most ancient Martian surface geology is well-preserved and observable with spacecraft, whereas nearly all the observable surface of Venus is probably younger than 1 GY (McKinnon et al., 1997). Abundant evidence exists for many kinds of water-formed features and deposits on the Martian surface. However, paradoxically, models of the early

Martian climate under the influence of the faint young sun do not produce surface temperatures warmer than the freezing point of water. This is at present an unsolved problem. Surface water on Mars may have been a transient or localized phenomenon, perhaps allowed by heating due to stochastic large impacts (Segura et al. 2002). Alternatively, the steady-state climate may have been warmer through mechanisms that are presently not understood. It is safe to say that the longevity of habitable surface conditions on Mars is currently not known and that therefore it is not known whether habitable conditions persisted for longer on Mars or Venus.

If one accepts that Venus started with a large, albeit currently unconstrained, water inventory, the first order question of Venus' evolution to its current state then becomes the question of water loss. Models of early atmospheric evolution have supported the idea that Venus may have lost most of its original hydrogen inventory through a phase of hydrodynamic escape fueled by the enhanced EUV flux from the early sun during a phase of runaway or "moist" greenhouse (Kasting et al, 1984; 1988) followed in turn by loss of hydrogen through various thermal and nonthermal escape mechanisms, including Jeans escape, charge exchange, collisional ejection (Kumar et al., 1983), and an electric field driven flow of ions in the night-side hydrogen bulge (Donahue et al., 1997).

The timescale for this loss of water has been suggested as several hundred million years (Kasting et al., 1984, 1988), but remains highly uncertain. Kasting et al. (1988) in many ways optimized his calculations to get rid of oceans quickly. These calculations provide an upper limit on surface temperatures during the moist greenhouse phase. This yields an upper limit on water fluxes to the upper atmosphere, and an upper limit to the resulting hydrogen escape fluxes. Therefore, it yields a lower limit on the lifetime of the ocean. Indeed, although the work of Kasting et al. (1984, 1988) currently represents the state of the art in modeling escape from early Venus, all of the uncertainties mentioned in this work add up to an overall uncertainty in the lifetime of the Venusian ocean that is larger than the lifetime of the solar system. Thus these calculations serve to show that it is possible, with known processes, to remove an FTO worth of water from Venus, but they do not provide a well-constrained estimate of the timescale for water loss.

One of the most difficult aspects of modeling the climate history and timescale for water loss on Venus is understanding the effects of clouds on the early environment. Cloud feedback is not included in any of the currently published models of the moist greenhouse. Yet, qualitatively, cloud feedback is expected to stabilize surface temperatures with rising solar flux, as cloud coverage and thickness increase with increasing temperature, and therefore albedo increases

as the planet warms. Therefore cloud feedback would be expected to extend the lifetime of the moist greenhouse.

Plate 1 shows the results of some very simple calculations of the effects of clouds on temperature structure on a planet with a CO_2-H_2O atmosphere. In order to test the notion that clouds could have played an important, even dominant role in the radiation balance of a warm, wet Venus we have developed simple 1-D, semi-gray, 2-component, 2-stream model of a wet Venus atmosphere. Lapse rates in the convective lower atmosphere are controlled by a wet adiabat, and water clouds are allowed to form where the atmosphere becomes saturated with water. We use simple analytic expressions to calculate the albedo and scattering properties of these clouds. We considered cases with 0, 50 and 100% cloud cover. To illustrate the effects of clouds, we have considered a 1 bar N_2 atmosphere with 350 ppm CO_2. Atmospheric H_2O is allowed to vary over many orders of magnitude, from 6 mbar to 60 bars. The full radiative-convective equilibrium temperature profiles, along with the locations and extent of clouds are shown in Fig. 1 for atmospheres with 6 mbar, 60 mbar, and 2 bar of H_2O. For 6 mbar, we obtain something like the surface temperature of present-day Earth, with clouds existing between 2 and 10 km. With 10 times this amount of water, the surface temperature is 100 K higher, and clouds inhabit the atmosphere at about 20 km. For the 2-bar H_2O case, the tropopause rises to about 50 km and surface temperatures are about the same as present-day Venus. For all these cases, we assume 100% cloud cover.

The results of these somewhat crude calculations suggest that clouds will indeed act to significantly cool the surface during the moist greenhouse phase. Since hydrogen escape rates depend sensitively on upper atmosphere water abundance, which is in turn strongly dependent on surface temperature, these results lead us to believe that cloud-albedo feedback will significantly prolong the lifetime of early Venusian oceans. In this light, it is interesting to note that there are no strong geological constraints on the longevity of Venus' oceans, beyond the observation that there are no obvious signs of surface water seen in the ~1 GY record recorded by the Magellan radar maps. Thus it is possible that the lifetime of Venus' oceans was measured in billions of years, rather than hundreds of millions. These considerations motivate a much more rigorous calculation of climate during the moist-greenhouse phase.

Based on these results, Grinspoon and Bullock (2003) suggested that with the increased stability of surface oceans provided against the warming sun by cloud-albedo feedback, it is quite possible that oceans may have persisted for substantially longer than the oft-quoted 600 MY, perhaps as long as 2 GY. Thus the surface of Venus may have been a habitable environment for a substantial fraction of solar

system history. The rapid rate of dissociation of water and subsequent escape of hydrogen may have resulted in an oxygen-rich atmosphere during this time. This is an intriguing possibility for astrobiology given the likelihood that the late evolution of multicellular life on Earth may have been due to the timescale for atmospheric oxygenation.

3. VENUS AND COMPARATIVE PLANETARY ASTROBIOLOGY

In the last decade upwards of 200 planets have been discovered orbiting other stars (Reid, 2007). Observational selection has resulted, as of this writing, in an absence of terrestrial planets with masses close to that of Earth among those observed. However, formation and dynamical models predict a large number of terrestrial planets (Raymond *et al.* 2006). As far as we know, with the possible exception of the existence of life on Earth, there is nothing very unusual about the solar system, so discovery and remote sensing of many extrasolar terrestrial planets is widely anticipated. These predictions will soon be testable, as data from the COROT and Kepler missions begin to reveal the demographics of terrestrial planets in our galaxy and more advanced observational programs make possible the study of the spectra and light curves of such bodies.

Given this expected harvest of terrestrial planet data over the coming decades, the importance of studying these worlds for putting Earth, and life, in context, and the certainty that knowledge of these planets will be restricted to remote sensing for the foreseeable future, it is vital that we have "ground truth" in the form of terrestrial planet studies that combine remote sensing with *in situ* exploration. Extrasolar terrestrial planets to be observed can be expected to sample a complete suite of evolutionary states representing early, mature and late phases of planetary history. This increases the importance of comparative studies of the current states and evolutionary histories of Venus, Earth and Mars. For understanding the possible evolutionary histories of Earth-sized planets, the Venus-Earth comparison represents a unique opportunity.

If experience of extrasolar planet discovery thus far is any guide, then the variety of terrestrial planets is likely to be large and surprising. Making sense of this diversity with such a small baseline of well-known local examples of terrestrial planet evolution seems like a daunting task. However, to the extent that we can reliably piece together the evolutionary histories of the local terrestrial planets, this task is eased by the fact that we then, in a sense, have more than three local examples. Exploration of the current terrestrial planets provides us with an increasingly detailed snapshot of planetary evolution at one moment of geological time around

a 4.55 billion year old G-type star. In the first billion years of solar system evolution, Venus, Mars and Earth were all very different from their current states, in ways that would be easily observable through remote sensing. To the extent that we can understand, with some confidence, the likely past and future states of local terrestrial planets, we can expand our knowledge base to more than the three examples provided by the current states of these planets.

In turn, when we have built up a sizeable database of observable characteristics of extrasolar planets around stars of different ages, it is likely that patterns will emerge which will help us to constrain our models of planetary evolution. Eventually we will have a database that will allow us to discern common classes of evolutionary pathways for terrestrial planets. As we discover and observe extrasolar terrestrial planets, we will see the full range of evolutionary stages and end states. We will undoubtedly see planetary systems of a wide variety of ages, from newly formed systems to "middle aged" systems like our own around stable main-sequence stars, to older planetary systems around late stage stars. These observations will help us to refine our understanding of the early histories and distant fates of Venus, Earth and Mars.

As our understanding of terrestrial planet evolution has increased, the importance of water abundance as a substance controlling many evolutionary factors has become increasingly clear. This is true of biological evolution, as the presence of liquid water is widely regarded as the key to the possibility of finding "life as we know it" on other worlds (Pace, 2001; Benner et al., 2004). It is also true of geological and climatic evolution. Water is among the most important climatically active atmospheric gasses on the terrestrial planets. It is also a controlling variable for tectonic style and geologic processes (Bercovici, 2003), as well as a mediator of surface-atmosphere chemical reactions (Walker et al., 1981). Thus, understanding the sources and sinks for surface water and characterizing the longevity of oceans and the magnitude of loss mechanisms on terrestrial planets of differing size, composition and proximity to stars of various stellar types, and the range of physical parameters which facilitates plate tectonics is key to defining stellar habitable zones.

As we learn enough through exploration and further modeling, to better characterize the evolutionary history of Venus, we will build a context for interpreting observations of extrasolar terrestrial planets. In particular, given the likelihood that Venus and Earth started out with similar surface conditions, and that Venus underwent loss of potentially one or several FTOs worth of water, the semi-controlled "experiment" of the apparently divergent histories of Venus and Earth is of particular interest for characterizing the histories and fates of Earth-sized worlds, and understanding

their dependence on initial conditions including stellar type, stellarcentric distance and initial volatile abundance.

It is striking that of the three local terrestrial planets, two have lost their oceans either to a subsurface cryosphere or to space, and one has had liquid oceans for most of its history. It is likely that planetary desiccation in one form or another is common among extrasolar terrestrial planets near the edges of their habitable zones.

On Venus, the very low abundance of water in the atmosphere and crust, combined with ongoing volcanism, have led to a sulfur-rich environment (Prinn 1985). This is most obvious in the globally-encircling sulfuric acid cloud layers, but there are strong experimental and observational reasons to believe that sulfur gases in the atmosphere interact vigorously with the surface (Fegley and Prinn 1989; Bullock and Grinspoon 2001; Prinn 2001).

Perhaps one of the most important discoveries about the history of water on Mars has been the very recent detection of massive layered sulfates by the Opportunity Mars Exploration Rover in Meridiani Planum (Squyres et al 2004a). These record not only the past existence of flowing surface water, but also the chemical nature of the water that was there last (Squyres et al. 2004b, 2005; Grotzinger et al. 2005). Meridiani sedimentary rocks are about 40% sulfate, with embedded nodules of hematite and significant quantities (a few percent) of the iron sulfate mineral jarosite (Clark et al. 2005). This implies that the sediments were laid down in highly acidic water, with a pH of between 2 and 4, when conditions were also oxidizing (Elwood Madden et al. 2003). The layered deposits in Meridiani, as seen from the Mars Observer Camera aboard the MGS spacecraft, are about 1 km thick and cover a region about the size of the Colorado Plateau (Hynek et al. 2002). It is very likely that they are the chemical remnants of an acidic sea. The history of Meridiani is probably not unique on Mars, as layered sulfate deposits are also seen in much larger quantities within Valles Marineris by the Omega spectrometer on the Mars Express Spacecraft (Gendrin et al. 2005). The lack of carbonate deposits of any kind strongly argues for a sulfur-rich, acidic environment as the last of Mars' surface water disappeared (Bullock and Moore 2005).

For large quantities of water to maintain a low pH on early Mars, they must have been supplied with sulfur, most likely from volcanism. Phillips et al. (2001) showed that the entire Tharsis bulge is a large igneous construct, emplaced mostly during the late Noachian era. The formation of Tharsis alone could have supplied enough sulfur to Mars' atmosphere to acidify the oceans and produce the chemical record that we see today. The early Martian atmosphere would very likely have hosted sulfuric acid/water clouds or hazes, much like Venus does today.

Both Venus and Mars have sulfur-rich environments, and may have experienced a watery past followed by an acidic phase as they desiccated. Current observations of Mars are thus leading to the increasing relevance of studying Venus as an early Mars analog. If there was an origin of life on Mars, it would most likely have taken place in acidic, sulfur-rich conditions.

Astrobiology, with its predecessor exobiology, has been accused of being a "science without a subject". This is not strictly true, as the subject includes the history of Earth, its comparison with other planets, and the origin, evolution and future of life. Nevertheless, the subject of life and its potential distribution in the universe is not informed by a large number of known examples. In fact, arguably, this is one of the few sciences based on a single example of a complex phenomenon (along with cosmology and perhaps evolutionary biology). Thus, it is important to question all assumptions about biology's universal characteristics which are based on the potentially unique qualities of Earth's biosphere, lest we slip into a kind of scientific solipsism, convinced through our ignorance and lack of perspective, rather than through actual evidence, that life elsewhere must share our own exact characteristics. Our planetary exploration, with an increasing focus on astrobiology, is designed to "follow the water". This is a reasonable strategy but it is based, at best, on an educated guess about life's universals. Such an approach is necessary, for now, for us to proceed with astrobiological exploration in the absence of other biological examples. Yet, in our current ignorance, all conclusions as to what is "universal" about life must be regarded as provisional. Given this philosophical problem, any alternative means of evaluating the habitability of planets should be given serious consideration. The most common means of evaluating planetary habitability begins and ends with the assumption that other planets, in order to be suited for life, must possess a similar environment to that of Earth, at least similar enough for liquid water to be present (see for example Schulze-Makuch and Irwin, 2003).

One alternative that has been suggested is the "Living Worlds Hypothesis" of Grinspoon (2003). According to this idea, life is not merely a local phenomenon that requires certain chemical or thermodynamic conditions in specific micro-environments to exist, but is best thought of as a planetary property. The only inhabited world we know of is so pervasively inhabited that it is difficult to find a terrestrial environment that has not been occupied by life, and probably impossible to find an environment that has not been modified by life. It is also true that the natural history of Earth is so deeply bound up with the history of life that it is almost meaningless to discuss the history of the "nonliving part" of Earth as a separate topic from the history of terrestrial life (Margulis and Lovelock, 1974). It cannot be argued, based on a statistical sample of

one, that because these are characteristics of life on Earth, that they should be universal characteristics of inhabited planets. That is, unless the longevity and stability of life on Earth are causally related to life here being a global property of the planet. If this were the case, then for example, the existence of Martian life persisting in isolated remnants of a former global biosphere which still retain liquid water and energy sources is much less likely (Grinspoon, 2003).

This viewpoint focuses attention on global properties, such as rate of exchange of matter and energy between interior and surface, surface energy gradients, available sources of free energy, magnitude of energy gradients, or atmospheric disequilibrium properties, that may be required for life to persist for geological timescales. In this light it is interesting to note that Venus and Earth share some global properties that may be relevant for this type of consideration. The global distribution of surface ages may serve as a crude proxy for total level of ongoing endogenous planetary activity. Although we have only a rough knowledge of the surface age distribution of Venus, it is clear that almost all surface units are younger than 1 GY, as is also true of Earth's surface. This is in marked contrast to Mars, the Moon, and Mercury, where almost all surface units are older than 3 GY. If we think beyond the specifics of a particular chemical system required to build complexity and heredity, we can ask what general properties an inhabited planet must possess. Judging from our sample of one inhabited planet, the answers might include vigorous geological activity continuing over billions of years, an atmosphere with signs of flagrant chemical disequilibrium and active, internally driven cycling of volatile elements between the surface, atmosphere and interior. At present, the two planets we know of which possess these characteristics are Earth and Venus.

In addition to the study of life's evolution and distribution, astrobiology also considers questions about the future of life. Does Venus have an astrobiological future? Given the slowly brightening sun and the continued exospheric loss of hydrogen it would seem that left to its own devices, the biological future of Venus is not a promising one. But will Venus always be left to its own devices? Several researchers have considered the possibilities of planetary engineering or terraforming Venus, or a Venus-like planet, altering its surface environment to be more conducive to organic life (Fogg, 1987; Dyson, 1989; Adelman, 1992; Pollack and Sagan, 1994). While an exploration of this speculative topic is beyond the scope of this paper, the interested reader is encouraged to pursue the available literature.

4. THE POSSIBILITY OF EXTANT LIFE

The common exercises of astrobiology each contain some, perhaps unavoidable, degree of geocentrism. Most reviews

of the possibility of life on Venus begin with an examination of terrestrial extremophiles which exhibit resistance to environmental extremes associated with the Venusian environment (Cockell, 1999). These include acidophiles, hyperthermophiles, organisms with unusual osmotic capabilities, pressure tolerance, radiation resistance, ability to survive unusual atmospheric compositions, and so forth. This approach is pragmatic in that it allows us to use data from known organisms to assess the habitability of extraterrestrial environments, but it is worth reminding ourselves that any organism found on another planet will most likely not be a terrestrial extremophile and the idea that alien organisms can only inhabit environments proscribed by the limits of terrestrial organisms is an untested and extremely conservative assumption.

Given the high danger of solipsistic, geocentric reasoning, it is a useful exercise to consider life in non-obvious locations, including those where it is generally considered unlikely. In this spirit, some researchers have persisted in arguing that extant life on Venus cannot be ruled out given our present ignorance about life's range and limits, and the current constraints on our knowledge of the Venusian environment (Grinspoon, 1997; Schulze-Makuch and Irwin, 2002; Schulze-Makuch et al., 2004).

These arguments have focused on the possibility of life in the global cloud decks of Venus. Properties of the Venus clouds which are potentially hospitable to life include the following: (1) the clouds form an aqueous environment. While water is scarce, water vapor concentrations reach several hundred ppm in the lower clouds, (2) the cloud region has temperatures of 300–350K and pressures around 1 bar. (3) the clouds are much larger, more continuous and stable than clouds on Earth (Grinspoon et al. 1993). At some latitudes the cloud particles do not fall at all, as vertical transport velocities are higher than fall velocities (Imamura and Hashimoto, 1998). Thus the particle lifetimes will be approximately equal to the Hadley circulation timescale of 70–90 days. This is several orders of magnitude longer than the typical division time of bacteria. ; (4) the atmosphere is in chemical disequilibrium, with H_2 and O_2, and H_2S and SO_2 coexisting; (5) the "mode 3" particles in the lower cloud, which dominate the mass of the cloud deck, may be non-spherical, and may contain an unknown, non-absorbing core material which comprises up to 50% by volume of the particles (Cimino, 1982; Grinspoon et al. 1993) and are comparable in size to microbes on Earth; (6) the superrotaton of the atmosphere enhances the potential for photosynthetic reactions by producing a day-night cycle of 4–6 days, compared with 117 Earth days on the surface. (7) the unknown UV absorber has some properties in common with a photosynthetic pigment (Grinspoon, 1997).

There are several obvious objections to the idea of life in the Venusian clouds, although each depends on unproven assumptions made from extrapolating the properties and limits of terrestrial life. One objection has been summarized as "Why aren't the clouds green on Earth?". In other words, if cloud-based life were possible, surely on Earth, where life is nearly ubiquitous and has demonstrated its exhaustive evolutionary opportunism, the clouds would show obvious signs of inhabitation. However, Grinspoon (1997) points out that on Earth clouds are a comparatively transient and fragmented niche, with typical particle lifetimes of days, as compared to months on Venus. Further, it has not been established that clouds on Earth are not an inhabited niche, and some researchers have found evidence for terrestrial cloud-based bacterial colonies. In experiments conducted at the Sonnblick Observatory at an altitude of 3106 m, Sattler et al. (2001) analyzed condensing clouds and found growth and reproduction of microbes in super-cooled cloud droplets. They concluded that the limiting factor for the persistence of microbial life in cloud droplets is residence time in the atmosphere. Thus, for water-based life it may be that, in terms of stability and continuity, the discontinuous and cold clouds of Earth represent a much more extreme environment for life than those of Venus.

Another common objection to the idea of life in the Venus clouds is that, although they are an aqueous medium, the cloud droplets are strongly acidic. All known terrestrial acidophile organisms rely on active trans-membrane proton pumps to maintain their cytoplasm at a pH between 4 and neutral. How strong an impediment to life is the high acidity of the sulfuric acid clouds? Supporters of possible Venusian cloud life point to the ever expanding range of known terrestrial acidophile organisms.

Interestingly, the first known representatives of extreme acidophiles (growing near pH 0) that were found were eukaryotes rather than prokaryotes (Hoover, 2006). *Cyanidium caldarium* is a red algae (a rhodophyte) that contains both chlorophyll "a" and C-phycocyanin in its chloroplasts. It colonizes most of the hot, acid soils and waters on Earth. Three other extremely acidophilic eukaryotes are fungi: *Aconitium cylatium*, *Cephalosporium sp.*, and *Trichosporon cerebriae* (Schleper et al., 1995). The green alga *Dunaliella acidophila* can survive pH 0, but the maximum for growth is at pH 1 (Pick, 1999).

The archaeon *ferroplasma acidarmanus* thrives at pH 0 (Edwards et al., 2000), This eubacterium has no cell wall and it grows at pH 0 in acid mine drainage in Iron Mountain in California. The cell membrane is the only barrier between the cytoplasm and concentrated sulfuric acid infused with high concentrations of copper, arsenic, cadmium and zinc. This is the current low pH record for bacteria.

Although even some chemistry textbooks state that negative pH is not possible, this is in error. The error comes from the common use of the hydronium (H_3O^+) ion to measure pH, and the consequent statement in many popular science textbooks and some textbooks that pH can only exist within a range between 0 and 14. However, pH, commonly defined as pH = -log[H^+] (negative the logarithm of the hydrogen ion molarity) is better defined as pH = -log a_H+ (negative the log of the hydrogen ion activity). In very strong acid solutions, where there are few water molecules per acid formula unit, the influence of the hydrogen ions in the solution is enhanced. Thus the effective concentration, or the activity, of the hydrogen ions is much higher than the actual concentration. This commonly leads to negative values of pH. For example, commercially available concentrated HCl solution (37% by mass) has pH ≈ -1.1. (Lim, 2006). Figure 1, from Nordstom et al. (2000) shows the dependence of pH on sulfuric acid concentration, when the hydrogen activity coefficient is properly included. Hot springs near Ebeko volcano, with naturally occurring HCl and H_2SO_4, have pH of ≈ -1.7, and acid drainage at the Richmond Mine at Iron Mountain, CA have been measured at -3.6. The latter are the most acidic waters found on Earth so far.

As seen in Plate 2, the relatively water-rich aerosols in the upper cloud have a small range of positive pH, from 0.3 to 0.5. In the lower cloud, with its larger and more water-poor particles, pH can be as low as -1.3. The aerosol H_2SO_4 concentrations were calculated using the cloud model of Bullock and Grinspoon (2001), constrained by Pioneer Venus data, with corrections for high activities from Nordstrum et al. (2000).

There are now many terrestrial organisms known that can survive in negative pH conditions. The most extreme hyperacidophiles known to date belong to the archaea. For example, *Picrophilus oshimae* and *P. torridus* are able to grow at pH –0.2. They grow within the moderately thermal regime and were discovered in Japan near hydrothermal springs with solfataric gases (Schleper et al., 1996).

There are settings on Earth with acidity that exceeds that in the Venus clouds. For example, at Iron Mountain, California, a superfund cleanup site where pyrite mining has produced waters which are extremely concentrated in sulfuric acid, a pH of -3.6 has been measured (Nordstrum et al., 2000). As the water flowing from this site mixes with fresh water it produces a gradient of increasing pH in the downstream direction. This creates an interesting experiment in extremophile biology. How far upstream, in the direction of decreasing pH, does life exist? Unfortunately, the answer is not yet known. Organisms existing in water at pH ~0 have been cultured. However, it is not easy to search for life in the more acidic waters in the negative pH zone of
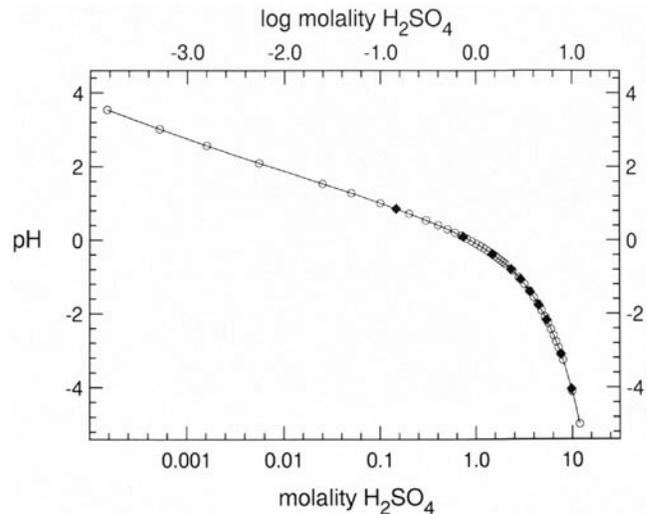

Figure 1. After Nordstom et al (2000). The dependence of pH on sulfuric acid concentration, when the hydrogen activity coefficient is properly included, calculated using the Pitzer ion interaction theory.

this stream, as ordinary culture mediums would simply dissolve in this water (Nordstrum, 2005). New, acid-resistant, culture mediums will have to be created in order to test for life in the most acidic waters. Thus, the low pH limit of terrestrial life is currently not known.

Another environmental constraint often mentioned as potentially prohibitive for life in the Venus clouds is the high UV flux, which would prove fatal for contemporary terrestrial surface organisms, as UV radiation is damaging to biological macromolecules. However, adaptation to high UV fluxes under selection pressure has been achieved by some terrestrial organisms. One strategy is the development of UV absorbing pigments such as carotenoids and scytonemin (Wynn-Williams et al. 2002). Other organisms have used layers of soil or water for protection (Pierson et al. 1993; Wynn-Williams and Edwards, 2000), or shielding by organic compounds from dead cells (Marchant et al. 1991). Still others, such as *Deinococcus radiodurans*, take a more active approach toward restoring UV damaged DNA and UV-sensitive proteins, repairing and resynthesizing macromolecules as needed (Battista, 1997; Ehling-Schulze and Scherer, 1999). The fungus *Fusarium alkanophylum* exhibits optimal growth under high does of UV radiation, provided that the growth medium contains sulfur-rich proteins (Marcano *et al.* 2002).

Given the evolutionary history of UV flux at the Earth's surface during the history of life, and the ability of many organisms to adopt to high UV fluxes, it is unlikely that the UV flux presents an impediment to life in the Venus clouds. Cockell (1999, 2000) points out that the UV flux in the
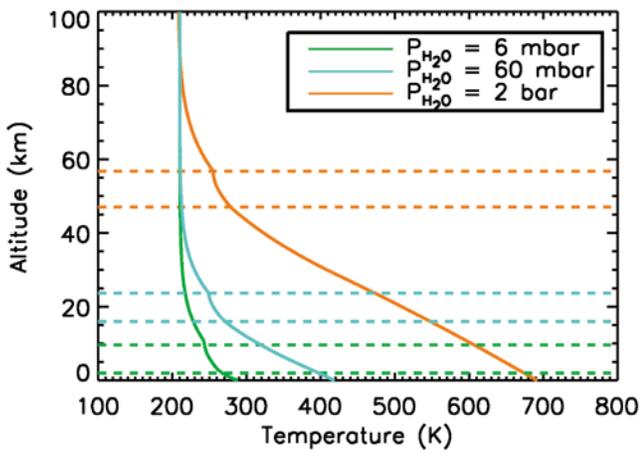
Plate 1. Radiative-convective equilibrium temperature profiles, as described in the text, along with the locations and extent of clouds for atmospheres with 6 mbar, 60 mbar, and 2 bar of H_2O.
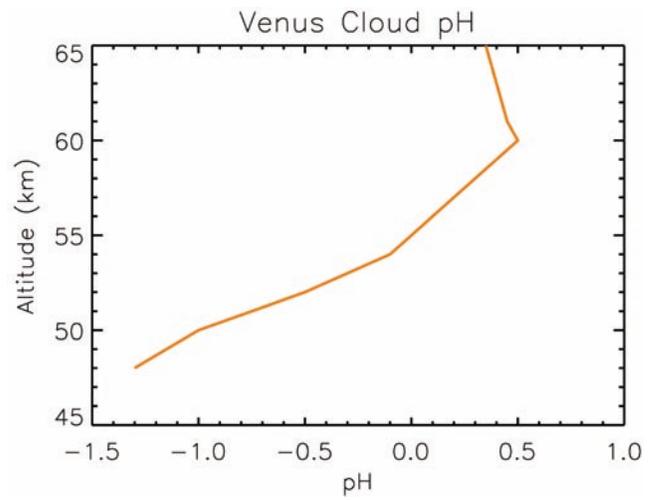

Plate 2. The pH of Venus' clouds as a function of altitude. The relatively water-rich aerosols in the upper cloud have a small range of positive pH, from 0.3 to 0.5. In the lower cloud, with its larger and more water-poor particles, pH can be as low as -1.3. Aerosol H_2SO_4 concentrations were calculated using the cloud model of Bullock and Grinspoon (2001), constrained by PV data. Correction for high activities is from Nordstrum et al. (2000).

upper clouds of Venus is comparable to the surface flux on Earth during the archean, before the build-up of atmospheric ozone but after the origin of life. Thus the UV flux cannot be considered to be a limit to the habitability of the cloud environment. In fact, it has been proposed that appropriately adapted organisms might use this flux as an energy source to power metabolism (Grinspoon, 1997; Schulze-Makuch et al. 2004).

Schulze-Makuch et al. (2004) proposed that cycloocta-sulfur (S_8) could be employed as a UV shield, and might also be employed as a UV-powered photosynthetic electron donor. They point out that S_8 is the most stable form of elemental sulfur within the clouds, and does not react with sulfuric acid. It absorbs strongly in the UV, with an absorption maximum at 285 nm, near the UV wavelengths most damaging to cells ($\approx$240–280 nm). The absorption is so strong that a few monolayers of S_8 would provide a significant UV shield for putative organisms. S_8 has been proposed as a UV shield on the early Earth (Pavlov et al. 2002). S_8 also reemits at visible wavelengths, providing another possible mechanism for photosynthetic exploitation of UV radiation.

Elemental sulfur might also be microbially produced by a photosynthetic reaction in which hydrogen sulfide is oxidized to elemental sulfur and carbon dioxide is reduced to organic carbon (equation 1)

$$2H_2S + CO_2 + light \rightarrow \text{``}CH_2O\text{''} + H_2O + 2\,S \qquad (1)$$

Many terrestrial organisms using this reaction thrive in marine sediments and hot springs (e.g. Vethanayagam, 1991, Bryantseva et al., 2000). The oxidized sulfur could then be polymerized to S_8. Several photosynthetic microbes, which use H_2S as their electron source, deposit sulfur outside the cell including Green Sulfur bacteria, some Purple Sulfur bacteria and some cyanobacterial species (e.g. Pierson et al., 1993; Tortora et al., 2001). Putative Venusian microbes might deposit elemental sulfur on the outside of their cells to convert potentially harmful UV radiation to electromagnetic frequencies that are usable for photosynthesis, or harvest the energy of UV photons through conversion to appropriate electron donors. Alternatively, they may just utilize sulfur allotropes as "sunscreen" and utilize visible light for photosynthesis. Schulze-Makuch et al. (2004) point out that while on Earth selection has favored photosynthetic mechanisms that operate at neutral pHs and are non-functional at high acidity, on Venus forms of life may have evolved different molecular machinery to deal with the progressively acidifying conditions.

Another concern about the habitability of the Venus cloud environment is that there is not sufficient access to the "biogenic elements". The biogenic elements are generally given as C,H,O,N,S,P as well as several trace metals, such as Co, Mn, and Mo. It seems dangerously geocentric to expect extraterrestrial life to require the exact same list of elements as life that has evolved in the near-surface environment of Earth, where these elements are available. Nonetheless, it can be pointed out that among the elements known to exist in the cloud region of Venus are C, H, O, N, S, P, Cl, F and most likely Fe. Among those suspected to exist are I, Br, Al, Se, Te, Hg, Pb, Al, Sb and As (Marov and Grinspoon, 1998). Thus the availability of a rich assortment of elemental building blocks, including most of the "biogenic elements" is not an impediment to possible life.

The previous arguments have been offered in defense of the proposition that life, once established, might be maintained in the clouds. It is harder to imagine an origin of life occurring in the cloud environment (though this may also be due to geocentric bias). Yet, as previously discussed, the surface of Venus, early in planetary history, may have had the necessary liquid water, organic rich, stable environment to support an origin of life, or survival of life that may have been transplanted from Earth or Mars through impact panspermia. As surface conditions became hostile, life could have adapted to an atmospheric niche under directional selection.

If we accept the premise that the present day clouds of Venus might be habitable, and that cloud life may have been implanted by lithopanspermia or migration from an ancient habitable surface, another question immediately presents itself. Have the clouds been continuously habitable over billions of years? It is not known whether the clouds have been a permanent feature of Venus. If Venus has been cloud free for any period of time then, in the absence of a habitable surface environment, life depending on the cloud niche could not have persisted. Today, the clouds form one continuous habitat and if they temporarily disappeared from the planet, there would be no refuge. Bullock and Grinspoon (2001) found that the lifetime of the global cloud deck against destruction by reaction of sulfur with surface minerals is 30 MY in the absence of replenishment of atmospheric SO_2 by volcanic outgassing. Thus, it is quite possible that Venus has gone through cloud-free epochs. In this case, a cloud-based biota would not have survived over planetary history. On the other hand, it is possible that the clouds have not disappeared but have at times become thinner, discontinuous and fragmented, before returning to their thick, globally continuous state. Such a history could theoretically have played a productive role in the evolution of Venusian biota by creating geologically significant time periods during which temporarily isolated environments would have facilitated increased speciation. Future missions to Venus and theoretical modeling of atmospheric and cloud evolution will illuminate the

global history of outgassing and the question of whether the clouds have been a continuous, stable environment over planetary history.

5. PLANETARY PROTECTION

At the dawn of the Space Age, as contamination of other planets with terrestrial biota (forward contamination) and contamination of Earth by alien microorganisms (back contamination) by vehicles of space exploration became a theoretical possibility, the scientific view of Venus was in transition. Attempts were made to interpret the anomalous microwave radiation thought (correctly) by some to indicate a surface temperature outside the range of liquid water. This is illustrated by the 1960 paper in *Science* "Exobiology: Approaches to Life Beyond the Earth", in which biologist Joshua Lederberg introduced the term "Exobiology" to the wider scientific community: "The habitability of Venus is connected with its temperature, a highly controversial subject. Perhaps the most useful first contribution to the exobiology of Venus would be a definitive measurement of its temperature profile. Even should the surface be unbearably hot, this need not preclude a more temperate layer at another level." In this seminal paper, Lederberg argued that "…we must *rigorously* exclude terrestrial contaminants from our spacecraft." and that the risk of back contamination, while apparently slight, must also be taken seriously, given the large magnitude of the potential consequences of error.

In the wake of the Mariner 2 results indicating surface conditions incompatible with organic life, planetary protection arguments and requirements for Venus missions were relaxed. In 1970, a study by the Space Science Board (the predecessor of the current Space Studies Board) of the National Research Council included quantitative estimates of the probability of contamination of Venus by an interplanetary spacecraft, and concluded that "A slight possibility exists that terrestrial organisms could grow on airborne particles near to the cloud tops of Venus… …Life on Venus is no more than a remote contingency, but the possibility of contamination by terrestrial organisms must be considered." This study recommended that only minimal precautions be applied to Venus bound spacecraft due to planetary protection considerations (Space Science Board, 1970).

A later study in 1972 (Space Science Board, 1972) similarly concluded that the probability of surface contamination of Venus by terrestrial spacecraft was effectively zero, and that the probability of growth of terrestrial microorganisms in the more temperate regions of the atmosphere was $\leq 10^{-6}$.

In 2005, in light of advances in astrobiology, including the discovery of extremophile organisms, new ideas about the possible viability of cloud-based life on Venus, and the prospect of a new generation of Venus spacecraft, NASA's Office of Planetary Protection, under the direction of Planetary Protection Officer John Rummel, decided to revisit the question of planetary protection protocols for Venus. The Space Studies Board's Committee on Origin and Evolution of Life (COEL) was asked to provide advice on planetary protection concerns related to missions to and from Venus, and a Task Group on Planetary Protection Requirements for Venus Missions was formed and heard expert testimony at several meetings. In particular, the COEL was asked to:

1. Assess the surface and atmospheric environments of Venus with respect to their ability to support Earth-origin microbial contamination, and recommend measures, if any, that should be taken to prevent the forward contamination of Venus by future spacecraft missions;
2. Provide recommendations related to planetary-protection issues associated with the return to Earth of samples from Venus; and
3. Identify scientific investigations that may be required to reduce uncertainty in the above assessments.

After hearing testimony and reviewing the relevant issues, the Task Group concluded, in summary, that:

- No significant risk of forward contamination exists in landing on the surface of Venus.
- No significant risk exists concerning backward contamination from Venus surface sample returns.
- No significant forward contamination risk exists regarding the exposure of spacecraft to the clouds in the atmosphere of Venus.
- No significant risk exists concerning atmospheric sample returns from the clouds in the atmosphere of Venus.

The task group thus recommended that the previous COSPAR Category II planetary protection classification of Venus be retained (see Attachment 2 in Space Science Board, 2006, available online at http://www.nap.edu/catalog/11584.html for full descriptions of these categories). Category II includes all types of missions to those target bodies where there is "significant interest relative to the process of chemical evolution and the origin of life, but where there is only a remote chance that contamination carried by a spacecraft could jeopardize future exploration." For category II bodies, the legal requirements are only for simple documentation. This required documentation includes a short planetary protection plan, primarily to outline intended or potential impact targets; brief pre-launch and post-launch analyses detailing impact strategies; and a post-encounter and end-of-mission

report providing the location of inadvertent impact, if such an event occurs.

For planetary protection concerns, the relevant question is ultimately not the probability of any habitable niche existing on present day Venus, but the likelihood that such a niche, if it does exist, possessing physical conditions which overlap the conditions under which terrestrial organisms can survive, grow and reproduce. The judgment of the ad hoc Task Group was that the chance of such overlap is too slight to significantly impact planning for future Venus missions. This is, in a sense, good news for the future astrobiological exploration of Venus as it means that such missions are not likely to be burdened with the cost and complexity of meeting complex planetary protection requirements.

6. FUTURE INVESTIGATIONS AND EXPLORATION

There are some investigations that can be undertaken on Earth to deepen our knowledge of possible life on Venus or Venus-like terrestrial planets. These would include further study of extremophile organisms, particularly those in highly acidic environments and environments requiring extreme osmoregulation for survival. Knowledge of the specific biochemical mechanisms that make these extremophilities possible, and the energetic costs of these adaptations would be particularly valuable in extrapolating these abilities to putative organisms in alien environments. Follow-up experiments must be conducted to further explore the provocative claims of Sattler et al. (2001) of finding reproducing bacteria in cloud environments on Earth, as well as thorough biological investigation of permanently cloudy environments on Earth, such as tropical cloud forests.

Another potentially revealing avenue of investigation might be attempts to grow terrestrial extremophiles in simulated Venusian clouds. The acidity of these droplets could be varied, as a simulation of the likely evolution of the Venusian cloud deck, in response to billions of years of volcanic outgassing, from a higher pH when the planet was dominated by water clouds during early escape of a steam-dominated atmosphere, to the extremely acidic current conditions. It would be very instructive to learn when, in the history of Venus history, the clouds became uninhabitable to terrestrial microorganisms, if indeed they are. These experiments would also be useful in the area of planetary protection, as tests of the prevailing view that the present-day Venusian clouds represent a sterilizing environment for organisms likely to be inhabiting spacecraft exteriors.

As long as our ignorance of Venus remains large, notions of exotic extant organisms will inhabit the gaps in our knowledge. The best way to put these speculations to rest is to more fully explore our sister planet. For example, once we have fully characterized the "mode 3" cloud particles and determined the composition of their core materials, then (assuming they do not turn out to be the home of Venusian bacterial communities) astrobiological speculation about their nature will greatly diminish.

Future missions to Venus can help to address astrobiological issues with observations clarifying the longevity of potentially habitable surface conditions as well as observations clarifying the conditions and history of the clouds of Venus and the closely coupled physical and chemical history of the interior/surface/atmosphere/cloud/climate system. Of particular interest for the astrobiological questions discussed in this chapter will be:

- Observations of stable isotopes, escape fluxes and their responses to the solar wind to test assumptions about similar Venus-Earth early water endowments and to constrain the subsequent divergent histories of hydrogen escape and climate change.
- Geochemical and geochronological observations constraining the global resurfacing history and the sulfur cycle, to test whether a cloud niche has been continuous, and whether disequilibrium chemistry in the clouds is compatible with more mundane geochemical and aeronomical explanations.
- Characterization of the unknown UV absorber and its relationship with sulfur chemistry.
- A more full characterization of the global atmospheric circulation and its effect on cloud particle lifetimes.
- Reliable measurements of trace constituents in the clouds and the surrounding atmosphere.
- Characterization of the surface rocks in the plains and tesserae, including their mineralogy, and searches for metastable hydrated minerals, zircons, and possible isotopic biomarkers.
- Determination of the ages of the major surface units.

This list of needed astrobiological observations from future missions is nearly identical to that desired to achieve a more general understanding of the planet and its evolutionary divergence from Earth. Venus is the only other example of an Earth-sized planet that we can hope to study up-close within the foreseeable future. We still don't understand how and when Venus diverged from a more Earth-like past, or how long Venus or Mars retained habitable conditions. If life begins easily on warm, wet planets (which seems to be the case, judging from Earth) then Venus probably once harbored Venusians. Did they die out as the climate changed? Venus can help us to understand the evolutionary paths that habitable planets can take. Further exploration of Venus will greatly advance our understanding of terrestrial planet habit-

able zones and "continuously habitable zones", and provide needed context for extrasolar terrestrial planet discoveries. What is good for planetary exploration of such a promising target—so Earth-like in bulk qualities but so alien in environmental evolution—is also good for astrobiology.

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