PART VIII
Initial Conditions for
Astrobiology

A general definition of life that is useful for remote exploration has proven elusive. As a practical matter, the search for life becomes the search for life as we know it, based on organic molecules in liquid water and a source of free energy. Organics are common in much of the solar system, so liquid water has become the focus of exobiological searches. Recent years have seen the discovery of the deep subsurface biosphere on Earth, some components of which appear to be entirely independent of surface conditions. It remains an open question whether life may in fact have originated in the subsurface. That possibility, however, suggests that deep liquid water environments, such as we now suspect exist on Mars and Europa, are plausible locales for extraterrestrial life. The most conservative requirement to set for extraterrestrial habitable environments is to require liquid water not at depth but, as with Earth, at a world's surface. The "circumstellar habitable zone" is defined as the volume of space around a star or star system within which an Earth-like planet could support surface liquid water. Although these zones change with evolving stellar luminosity, there is a significant habitable zone lasting for gigayears for stars with masses between 0.1 and 1.5 times the mass of the Sun. Therefore, even a conservative definition of habitability suggests many locales for life around other stars. Possible subsurface environments for life only expand the possibilities for biology even further.

I. HABITABILITY AND LIFE

A. Habitable for Whom?

The notion of planetary "habitability" was originally used to refer to conditions suitable for human life (Dole 1964). The word has since come to imply less stringent conditions, roughly those necessary for stability of liquid water at a world's surface (see section III below for a precise formulation). Prior to the elucidation of Earth's subsurface biosphere (discussed in

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section II), this could be viewed as the key necessary condition for simple microscopic life. Clearly, whether we regard a world as habitable depends in part on who or what will be doing the inhabiting. If we were interested in conditions specifically suitable for, say, forests (Heath 1996), still different requirements might be applicable.

On Earth, life had existed for about 3 Gyr before metazoa (multicellular animals) appeared (Runnegar 1992). Animals, plants, and fungi are multicellular, eukaryotic organisms. Eukaryotes are cells containing well-organized nuclei and other characteristic internal structures. Most multicellular life on Earth is eukaryotic, though there are also many eukaryotes that are single-celled. In addition to the eukaryotes, there are two other known broad domains of terrestrial life, the bacteria and the archaea, which are prokaryotes: cells lacking nuclei. Most prokaryotes are single-celled, but multicellular prokaryotes also exist, such as the filamentous bacteria and fruiting myxobacteria; some of the latter can form differentiated structures of $\sim 10^9$ cells approaching a millimeter in height (Madigan et al. 1997). Some of the oldest known microfossils (dating from 3.4 to 3.5 Gyr ago) resemble filamentous bacteria (Schopf and Walter 1983). Prokaryotes exhibit a wide variety of metabolic styles, deriving their energy from diverse electron donors and acceptors (fuels and oxidants), but eukaryotes require free molecular oxygen as their terminal electron acceptor (Nealson 1997a,b). This gives eukaryotes a substantial advantage in energy produced per carbohydrate molecule metabolized over those many prokaryotic organisms that cannot use O_2 (Day 1984), but at the price of requiring an oxic environment. In this sense, Earth may not have been habitable for eukaryotes until the rise of free oxygen in the atmosphere, beginning about 2 Gyr ago (Des Marais 1994, 1996).

A terrestrial atmosphere containing abundant free oxygen seems to have required aeons of oxygen production by photosynthesizing bacteria, as well as the oxidation of reductant sinks, and ultimately the burial of large quantities of organic carbon (Des Marais 1994, 1996). One is free to imagine worlds in which these processes required far less time than they did on Earth (McKay 1996), with eukaryotic analogs therefore able to arise much more quickly. Even so, it seems likely that at a given moment many more worlds will be home to single-celled organisms than, say, to metazoa. The most broadly useful definition of "habitability" will therefore be one appropriate to the simplest organisms that we would consider to be alive. But how do we distinguish life from nonlife?

B. Definitions of Life

A satisfactory general definition of life has proven elusive (Chyba and McDonald 1995), and one philosopher of science has even argued that a complete definition is impossible (Küppers 1990). Surely one reason for this pessimism is the historical fact that most attempts at a definition have failed. Sagan (1970) reviewed physiological, metabolic, biochemical, genetic, and thermodynamic definitions of life, but, as he pointed out, each

of these definitions faces problems, often in the form of counterexamples: either entities that fit the definition but that we would be reluctant to call alive, or organisms that are clearly alive but that the definition excludes. Nor is it sufficient to claim that a particular counterexample is "unimportant"; such a claim merely implicitly invokes other criteria in addition to the ostensible definition that has been proposed.

Consider, for example, a metabolic definition of life. A metabolic definition "describes a living system as an object with a definite boundary, continually exchanging some of its materials with its surroundings, but without altering its general properties, at least over some period of time" (Sagan 1970). But fire seems to fulfill these properties, and indeed the chemical reaction by which flames maintain themselves, combining organics with molecular oxygen, is similar to the metabolic reaction that fuels eukaryotic organisms.

1. The Darwinian Definition. There is a working definition of life, which we call the "Darwinian definition," that is becoming accepted within the origins-of-life community (Chyba and McDonald 1995). A careful formulation (Joyce 1994) is: "Life is a self-sustained chemical system capable of undergoing Darwinian evolution." The heart of this definition is its insistence on the importance of Darwinian evolution: self-reproduction, genetic variation, and natural selection. Its strength is its distillation of the objectives of ongoing laboratory experiments that seek to devise, through directed molecular evolution, a system of RNA or other molecules that are capable of self-replication, and evolve according to natural selection (von Kiedrowski 1986; Joyce 1993; Breaker and Joyce 1994). The view that "the origin of life is the same as the origin of Darwinian evolution" is becoming commonplace. Once Darwinian evolution is established, other diverse attributes of life may arise through natural selection.

Whatever its utility for laboratory experiments, the Darwinian definition faces serious drawbacks in the context of a remote search for life (Fleischaker 1990; Chyba and McDonald 1995). How long would we wait for a system to demonstrate whether it is "capable" of undergoing Darwinian evolution? The Darwinian definition, while useful in a laboratory setting, must give way in spacecraft exploration to a much less precise, but operationally more useful definition.

2. Lessons from the Viking Biology Package. Controversies over the definition of life have implications for laboratory and spacecraft experiments. Consider the three experiments in the *Viking* biology package (Klein et al. 1976; Klein 1977, 1978; Horowitz 1986). The experiments established broad criteria for the detection of life, based on the assumption that martian life could be recognized through its metabolism. For example, the labeled release (LR) experiment looked for organisms that would ingest any of a brew of organics provided by the experiment and metabolize one or more of them into a carbon-containing gas (Levin and Straat 1981*b*).

The results of the biology package, and especially those of the LR experiment, gave tantalizing results that in some respects mimicked life. Indeed, the head of the *Viking* biology team has noted that "if information from other experiments on board the two *Viking* landers had not been available, this set of data would almost certainly have been interpreted as presumptive evidence for biology" (Klein 1978). But a biological interpretation was undercut by an instrument not formally part of the biology package. The *Viking* gas chromatograph/mass spectrometer (GCMS) searched for organic molecules but found none at the ppm (for one- and two-carbon compounds) to the ppb (for more than two carbons) level, not even those that had been expected from estimates of micrometeorite infall (Biemann et al. 1977). Levin and Straat (1981*a*) have argued that some Antarctic soil samples contain no organics detectable at the level of the *Viking* GCMS but nevertheless yield a biological response from the LR experiment, suggesting a low level of microbial life that might be analogous to the situation on Mars. Nevertheless, the absence of organics, and the results of the *Viking* biology experiments, are now widely viewed as due to the action of organic-destroying oxidants produced in the martian atmosphere and surface (Hunten 1979).

The use of the GCMS as a life detection experiment approached the search for life on Mars from a perspective different from that of the biology package experiments. Whereas the latter relied upon a metabolic definition of life, the GCMS allowed a search for life based on a biochemical definition. Viewed as a life detection experiment, the GCMS simply assumed that life elsewhere would, like life on Earth, be based on organic molecules: No organics, no life. [The converse is certainly not true: The mere presence of organics does not imply the presence of life. To the contrary, it is now clear that organics are common molecules throughout the solar system and indeed the interstellar medium (Cruikshank 1997; Pendleton and Chiar 1997).]

One lesson from the *Viking* experience is the value of searching for life from the perspectives of different definitions. A second lesson from the *Viking* missions is the importance of the chemical and geological context for the interpretation of biological experiments. A third is the value of designing life detection experiments to provide useful information even in the case of a negative result.

Extrapolating from the *Viking* experience, the biochemical definition of life seems likely to trump all others in a remote sensing context. In the absence of compelling organic biomarkers, other biologically suggestive experimental results are likely to be distrusted or dismissed. One possible exception to this general conclusion might come from a microscopic exploration (Lederberg 1960, 1965) that imaged entities doing something unambiguously alive, such as propelling themselves or reproducing. In any case, but especially in the absence of detailed biochemical information, the importance of excluding the possibility of forward contamination is abundantly clear.

II. LIFE AS WE KNOW IT

Various techniques for the remote detection of life have been discussed since the dawn of the space age (see, e.g., Lederberg 1960, 1965). Even at the close of the 20th century, however, it may still be wisest to emphasize the central requirements for life as we know it: a source of free energy, a source of carbon, and liquid water. There were abundant terrestrial and solar sources of energy available for the origin of life on Earth (Miller and Urey 1959; Chyba and Sagan 1992, 1997), and analogs of many of these could be available and significant on other worlds within or beyond our solar system. Carbon-based molecules are also common, though not ubiquitous, throughout the solar system. But the *sine qua non* of life as we know it, and the requirement that appears the hardest to find is liquid water.

A. Why Water?

Even given an appropriate carbon source and copious sunlight or other energy, terrestrial life apparently absolutely requires liquid water (Mazur 1980; Kushner 1981; Horowitz 1986). This also seems to be the lesson of the dry valleys of Antarctica, which are among the harshest deserts on Earth and include areas where no microorganisms seem to exist outside of specific, protected habitats (McKay 1986; Campbell and Claridge 1987), although these claims largely rest on traditional microbial culture methods rather than on modern DNA amplification techniques (Vishniac 1993). From an operational point of view, then, the search for life beyond the Earth begins with the search for liquid water. Where there is liquid water, there is at least the possibility that life as we know it could exist. (Of course, life elsewhere might not prove to be at all "as we know it," but in that event it is hard to provide useful criteria to select among possible places to search.) As we will see in section III below, the requirement for liquid water is the key to the usual definition of habitability.

Why is life so dependent on liquid water? Cellular life requires an internal medium within which molecules may dissolve and chemical reactions may occur. Water has been called the "universal solvent," because of its ability to form hydrogen bonds with polar solutes (Blum 1962). A few other comparably good polar solvents exist, such as liquid ammonia (Barrow and Tipler 1986), and on much colder worlds, where water would be frozen but ammonia a liquid, ammonia might play the role for life that water plays on Earth. However, a biochemistry employing ammonia as a solvent would likely proceed far more slowly than its terrestrial counterpart, because of the typical Arrhenius exponential dependence of chemical reaction rates with temperature. One is also free to imagine an exotic biology (perhaps on Saturn's moon Titan?) whose solvent was liquid hydrocarbons. But hydrocarbons are nonpolar molecules, so any such biochemistry would be so different from that of terrestrial life that such speculations are currently scarcely constrained.

Water is also fundamental to terrestrial life because of its effect on the three-dimensional shapes of enzymes. Enzymes are proteins that catalyze chemical reactions, and like all proteins, they are made by linking together amino acids. Amino acids have side chains of atoms that may themselves be polar or nonpolar. In solution, different amino acids in the sequence of amino acids constituting the enzyme will be influenced by the surrounding water molecules according to the polarity of their side chains. Water is therefore crucial to enzymes' assumption of specific three- dimensional shapes, the shapes that confer to the enzymes their catalytic function.

Finally, liquid water has many important global effects. For example, water has an extremely high specific heat, so Earth's oceans provide an important moderating influence on the climate. Ice floats, so lakes and oceans freeze from the top down and are therefore more likely to thaw annually. [Solid ammonia, incidentally, does not float on its liquid phase (Wald 1964; Barrow and Tipler 1986).] These global effects no doubt seem pleasant to creatures such as ourselves that have evolved on a water-covered planet, but it is hard to see how any of them represents a requirement for the origin of life. This contrasts with the "microscopic" attributes of liquid water previously discussed, which do suggest that life based on liquid water may be the cosmochemically most likely version. Of course, this conclusion, based as it is on extrapolations from a single example, could ultimately prove to be mistaken (see, e.g., Feinberg and Shapiro 1980), but it gives us a place to start, and a conservative one: Were it possible to base life on liquid ammonia or hydrocarbons, for example, a liquid-water criterion for life would at worst have underestimated the scope for biology.

B. Liquid Water and Habitability in the Solar System

Earth provides the example of the kind of world on which traditional definitions of habitability (see section III below) rest: Liquid water on Earth is stable at the surface, and has probably been stable (with the possible exception of brief intermittent freezes; Hoffman et al. 1998) since early in Earth's history. Mars, on the other hand, presents a world that may once have allowed liquid water at its surface but has since apparently become a dry and frozen desert (Carr 1996; McKay and Stoker 1989; Goldspiel and Squyres 1991). If life exists on Mars today, it must have retreated to special surface or subsurface niches where liquid water remains possible (Boston et al. 1992).

Jupiter's moon Europa may well harbor a volume of liquid water equal to that in Earth's oceans, hidden beneath kilometers of surface ice (Carr et al. 1998). The geological evidence for a subsurface ocean on Europa is suggestive, but not decisive (Pappalardo et al. 1999). The hypothesis is, however, consistent with data from the *Galileo* spacecraft's magnetometer experiment (Khurana et al. 1998). Results from the latter experiment also imply a subsurface salty ocean within Jupiter's moon Callisto (Khurana et al. 1998), suggesting that subsurface liquid water may be a common fea-

ture of large icy moons. The planned 2003 Europa orbiter mission (Johnson et al. 1999) and possible subsequent lander missions (Chyba et al. 1999) should determine whether an ocean really exists on Europa, and begin the search for signs of life.

Could there be sites of hydrothermal activity on Saturn's moon Titan, a world the size of Mercury? Titan is rich in organic molecules, produced in its nitrogen-methane atmosphere by ultraviolet and charged-particle processing (Sagan et al. 1992). If hydrothermal sites were also present, Titan would become an extremely important candidate not only for pre-biotic chemistry, but for extraterrestrial biology as well. The upcoming *Cassini/Huygens* mission should begin to tell us what lies beneath Titan's pervasive organic haze layer (Matson 1997; Lebreton 1997).

Other liquid water environments may exist, or may once have existed, in the solar system. In particular, large asteroids and comets may have harbored liquid water environments in their deep interiors for up to the first $\sim 10^8$ yr of solar system history (Zolensky and McSween 1988, Podolak and Prialnik 1997) . This timescale is of interest because it is comparable to that available for the origin of life on Earth (Sleep et al. 1989). How-ever, it is unlikely that any putative asteroidal or cometary life that may have originated during this early liquid water phase could still be viable, because of the subsequent 4.5 Gyr of radioactive decay in the minerals composing the object and the resulting accumulated radiation damage in a frozen organism unable to repair itself (Clark et al. 1999).

C. Life at Depth

If life could exist only on worlds where liquid water were stable at the sur-face, then the only environment for life in our solar system would be Earth. However, the last two decades have revealed the existence of a terrestrial "deep, hot biosphere" (Gold 1992) in addition to the more evident one at Earth's surface. Estimates of the total mass of the subsurface biosphere (Whitman et al. 1998) suggest that it may be comparable to the surface biomass ($\sim 8 \times 10^{17}$ g, of which $\sim 10^{15}$ g resides in the oceans).

The mass of the surface biosphere is dominated by multicellular eu-karyotic organisms (mostly trees), dependent on free oxygen (Hayes et al. 1983). As one moves down into the subsurface, the eukaryotes quickly drop away as the oxygen level declines, and one enters the realm of the prokaryotes (Nealson 1997a,b). The extensive deep biosphere implies that eukaryotes may not dominate the terrestrial biomass. Primary production of organic matter remains likely to be dominated by the surface biosphere, which has access to orders of magnitude more free energy (as sunlight) than does the subsurface biosphere.

The critical question for the exobiological implications of the deep biosphere is the extent to which subsurface ecosystems are independent of surface life and conditions. In 1995, Stevens and McKinley (1995) re-ported the discovery of methanogenic microbes in samples drawn from 1.5 km beneath the surface of the Columbia River basin in Washington State.

These organisms seemed to obtain their energy from the oxidation by carbon dioxide of hydrogen derived from the weathering of basalt and ground water. If correct, this would provide evidence for subsurface microbial life that could exist entirely independently of surface photosynthesis. No free oxygen, ultimately derived from photosynthesis, appeared to be needed. Neither were any previously synthesized organics (also likely to be ultimately dependent on surface photosynthesis) needed to serve as electron donors; hydrogen produced by the interaction of anoxic water and rock seemed to fulfill this role. Carbon dioxide served as the sole carbon source. The Sun could disappear, and with it Earth's surface biosphere, and at least these microbes would continue to thrive, provided only that the terrestrial geothermal gradient maintained a subsurface region of liquid water.

However, subsequent experimental work found no significant H_2 production from the interaction of water with basalts from Snake River, Idaho (Anderson et al. 1998), contradicting conclusions from the initial experiments by Stevens and McKinley (1995). If correct, this suggests that the Stevens and McKinley methanogens may in fact be fueled by some other source of H_2, which may or may not be independent of the surface biosphere. The extent to which the subsurface biosphere is independent of surface photosynthesis remains a critical question. To date, we have only begun to sample the deep biosphere (Nealson 1997a,b; Whitman et al. 1998), and probably have nothing approaching a comprehensive understanding of its organisms or its metabolic diversity.

If some terrestrial life exists or can exist independently of surface photosynthesis, then the possibilities for deep biospheres on worlds such as Mars greatly expand. If life originated on Mars during its earlier, apparently more clement period (McKay and Stoker 1989), it would be possible that its progeny remain in subsurface niches associated with ongoing hydrothermal activity.

D. Can Life Originate at Depth?

In the preceeding section we asked whether life, once having originated at the surface of a world, could expand into subsurface niches and evolve at least some ecosystems that became entirely independent of surface conditions. A more fundamental question is whether life can *originate* at depth, independently from the Sun. If not (if, for example, the origin of life were to require the abundant energy available from sunlight), then only worlds that have clement surfaces (such as Earth) or that once did (such as Mars) could host extant ecosystems. But if the origin of life could occur at depth, then any world with subsurface liquid water would become a candidate for Earthlike (at least prokaryotic) life. In particular, worlds such as Europa would become prime candidates for contemporary biospheres.

A small amount of sunlight, filtering through the ice at young cracks, may be available to drive biology at Europa (Reynolds et al. 1983, 1987; Oró et al. 1992). Because the energy flux from sunlight at these cracks

could be several orders of magnitude greater than the average energy flux from Europa's core, even if life first originated at depth on Europa, there would have been a powerful energy incentive for it to evolve to areas of recent cracks or other areas of thin ice.

1. Hydrothermal Vents as Sites for Origins. Soon after the discovery of hydrothermal ecosystems at submarine thermal springs (Corliss et al. 1979), hydrothermal vents were proposed as a possible site for the origin of life on early Earth (Corliss et al. 1981). Suboceanic vents are attractive sites for the origin of life because of the associated presence of chemical reducing power in the form of minerals (Wächtershäuser 1988*a,b*; Holm 1992), and the protection they afford from all but the largest giant impacts (Maher and Stevenson 1988; Oberbeck and Fogleman 1989; Sleep et al. 1989). Controversy persists over whether the high temperatures characteristic of vents allow the synthesis (Shock 1990, 1992; Hennet et al. 1992) or require the thermal decomposition (Miller and Bada 1988) of prebiotic organic polymers. But substantial experimental progress is beginning to be made using the sort of iron and nickel sulfide minerals that currently collect near the vents as catalytic agents for prebiotically interesting reactions.

Wächtershäuser (1988*a,b*, 1990) proposed that synthesis of prebiotic organics on early Earth could have occurred through the reduction of aqueous dissolved CO_2 to organic compounds on iron and nickel sulfide mineral surfaces; the energy for these reductions would, for example, be provided by the exergonic formation of pyrite (FeS_2) from FeS and hydrogen sulfide (H_2S). Negatively charged organic acids would be electrostatically held to the surface of the positively charged pyrite, and a kind of "surface metabolism" would develop. This hypothesis faces a number of objections (de Duve and Miller 1991; Chyba and McDonald 1995), but it has inspired a list of successful experiments. For example, metallic iron can reduce N_2 to ammonia (NH_3) via the formation of iron oxides in the presence of liquid water at temperatures between 300 and 800°C (Brandes et al. 1998). Activated acetic acid can be synthesized by mixing carbon monoxide (CO) and H_2S with a slurry of nickel and iron sulfide particles at 100°C (Huber and Wächtershäuser 1997); that is, this environment can catalyze the fixation of inorganic carbon to organic carbon. While amino acid synthesis has not been demonstrated, it has been shown (Huber and Wächtershäuser 1998) that if amino acids were present under these conditions, they could be linked together to form short peptides. The problem of peptide formation has been a fundamental problem in the origin of life that had largely resisted solution under prebiotically plausible conditions. While these experiments remain far from demonstrating the origin of life at depth, they do represent an ongoing research program, motivated by this hypothesis, that is showing significant successes.

2. Meteoritic Evidence. Certain meteorites provide us with the only extraterrestrial examples, apart from ancient Mars, where liquid water was once available. There is substantial evidence for preterrestrial aqueous

alteration in carbonaceous chondrite meteorites, both from mineralogy (Grimm and McSween 1989) and from their amino and hydroxy acid profiles, which suggest that they formed by Strecker synthesis, requiring liquid water (Peltzer et al. 1984; Cronin 1989). While models of the thermal history of asteroids suggest that large ($\sim$100 km) objects could have maintained liquid water interiors for $\sim10^8$ yr, it seems likely that the Murchison meteorite, whose organic chemistry is the best studied of all the meteorites, experienced liquid water for much less time than this, perhaps $\sim10^4$ yr (Peltzer et al. 1984; Lerner 1995).

Carbonaceous chondrites are of potential interest because they represent actual examples of prebiotic organic synthesis in subsurface hydrothermal environments. Early in their history, carbonaceous chondrites hosted liquid water in the presence of the organic monomers (such as amino acids) needed for biomolecular synthesis, as well as potentially catalytic clay mineral surfaces. Yet abiotically produced peptides or oligonucleotides have not been reported. Cronin (1976) searched for small peptides in Murchison and concluded that no more than 9 mole percent of the total acid-labile amino acid precursors in the meteorite were peptides. Does Murchison therefore mean that liquid water, prebiotic organic monomers, and mineral catalysts together for $\sim10^4$ yr are insufficient for further progress toward the origin of life? If so, does this argue against the possibility of a deep subsurface origin, or does it point instead to some critical ingredient that Murchison is missing? Are there other carbonaceous chondrites in our collections that experienced liquid water for timescales orders of magnitude longer than did Murchison, and what do they show? These are important questions at the interface of planetary science and prebiotic chemistry (Chyba and McDonald 1995).

3. The RNA World. The prebiotic formation of peptides from individual amino acids is far from the only dilemma facing hypotheses concerning the origin of terrestrial life. As a second example, consider the "RNA world" hypothesis (Gilbert 1986). The discovery that certain sequences of ribonucleic acid (RNA) could exhibit catalytic activity (Zaug and Cech 1986) resulted in a proposed solution to an outstanding "chicken-or-egg" problem in origin-of-life research (Dyson 1985). The problem had been that in modern organisms deoxyribonucleic acid (DNA) carries the genetic information that codes for the sequence of amino acids that make up biological proteins, whereas proteins are needed for the replication of DNA. Which could possibly have come first? The RNA world hypothesis suggested that our current DNA-protein world was preceded on early Earth by one in which both the functions of genetic information storage and catalytic activity were carried out by RNA alone.

Although it is an important step forward (Joyce 1991; Joyce and Orgel 1993), the RNA world hypotheses faces numerous difficulties (Joyce 1989). In sum, under prebiotically plausible circumstances, it is hard to synthesize the right components for RNA; it is hard to put these components together to make RNA; and it is hard for RNA to re-

sist thermal decomposition for very long once it has formed (Chyba and McDonald 1995).

The existence of so many uncertainties in the RNA world and other hypotheses for the origin of life renders it difficult to use these hypotheses to reach compelling conclusions about the kinds of worlds on which Earth-like life could or could not originate. In the face of these uncertainties, it is probably best to return to simple fundamental criteria, such as the presence of liquid water, in order to select places to pursue the search for extraterrestrial life.

E. An Expansive View of Habitability

Given our current, still quite tentative knowledge about the prebiotic syntheses needed for the origin of life, we cannot say with confidence whether life would in general originate at depth, at the surface of a world, in either location, or whether both are needed together (Chyba 1998). The most conservative course remains to search for worlds like the Earth where surface liquid water exists. The remainder of this chapter will be devoted to estimating the extent and frequency of such environments. If even this conservative definition of habitability suggests many locales for life around other stars, then whatever we have ignored will only broaden an already substantial potential biological arena (Sagan 1996). However, we should bear in mind that this view of habitability may in fact prove far too conservative. As a practical matter, within our own solar system our gaze should linger upon any world that harbors liquid water at any depth. Beyond our solar system, those worlds that we are most likely remotely to recognize as habitable will probably be worlds that satisfy the more conservative definition.

III. CIRCUMSTELLAR HABITABLE ZONES

A. A Conservative Definition of Habitable Zone

We define the circumstellar habitable zone (HZ) as the volume of space around a single or multiple-star system within which an Earth-like planet could support surface liquid water. An Earth-like planet is one similar in mass and composition to Earth and having comparable surface inventories of CO_2, H_2O, and N_2 (Kasting et al. 1993; Whitmire and Reynolds 1996). The upper planetary mass limit is not well constrained, but the lower mass limit must be large enough to maintain sufficient geological activity to power the climate-stabilizing carbonate-silicate negative feedback cycle (Walker et al. 1981; Kasting 1988). If we require stability for ≥ 1 Gyr, then a mass greater than ~ 0.1 $M_\oplus$ is necessary, by analogy to the geological history of Mars (see III.B). The HZ evolves in time as the star's luminosity evolves (Kasting et al. 1993; Whitmire and Reynolds 1996).

If there were a real Earth-like planet in the HZ, then, by definition, it would have the compounds necessary for life. However, just the existence

of a ~1-$M_{\oplus}$ terrestrial planet in the HZ would not imply that it is inhabited or even habitable. For example, the role of impacts in planetary habitability is only just becoming understood (Chyba 1996*a,b*). Other considerations (see section V) are the possible extreme obliquity variations in the absence of a large stabilizing moon (Laskar et al. 1993; Williams and Kasting 1997) and synchronous rotation of planets around M stars (Joshi et al. 1997).

The continuously habitable zone (CHZ) is defined as that volume of space around a single or multiple-star system within which an Earth-like planet could support surface liquid water for a specified period of time. The CHZ is smaller than the HZ and it also evolves in time (Kasting et al. 1993; Whitmire and Reynolds 1996).

B. Evolution of the Sun's Habitable Zone

In the standard solar model, the Sun began its life on the zero-age main-sequence (ZAMS) with a luminosity of 0.7 $L_{\odot}$ and a photospheric temperature a few hundred degrees less than the present value. Compared to today, the early Sun probably rotated much faster, had a stronger and more active magnetic field and solar wind, a greater emission of X-ray and UV radiation, and a larger fraction of its surface covered with sunspots. The Sun's main-sequence lifetime is 11 Gyr (Sackmann et al. 1993), by the end of which its luminosity will have increased to 2.2 $L_{\odot}$. Upon core hydrogen depletion, the Sun will ascend the first red giant branch. Our interest here is primarily the evolution of the Sun's HZ during the main-sequence phase. The evolution of the HZ during the post-main-sequence phases was discussed and illustrated in Kasting et al. (1993) and Whitmire and Reynolds (1996).

Given the luminosity and temperature as a function of time, the evolution of the HZ can be calculated for specific values of critical fluxes defining the inner and outer boundaries from $S_1(T) = L(t)/r_1^2$ and $S_2(T) = L(t)/r_2^2$, where $r_1(r_2)$ is the inner (outer) HZ boundary radius, $L(t)$ is the solar luminosity as a function of time, obtained from the stellar evolutionary model, and $S_1(S_2)$ is the appropriate critical solar flux, which in general is a function of stellar temperature. The HZ radii will be given in units of AU when the luminosity is in solar units and the flux is in units normalized to the present solar constant at Earth's orbit, taken to be 1360 W m^{-2}.

Kasting et al. (1993) identified three critical fluxes for the inner radius of the HZ. In flux units normalized to the present solar constant these limits are 1.1, 1.4, and 1.76. The first two result from the loss of planetary water by the moist greenhouse and runaway greenhouse, respectively (Kasting 1988). These are theoretical values obtained from a one-dimensional radiative-convective climate model in which the radiative effect of clouds is parameterized by use of a high surface albedo. This assumption is expected to result in conservative limits; a real planet can probably maintain liquid water at a higher solar flux than calculated. The third limit is empirical and corresponds to the flux at Venus 1 Gyr ago. Spacecraft observations

show no evidence that liquid water has flowed on the surface of Venus for the last 1 Gyr (Solomon and Head 1991). This flux limit is an upper bound, because Venus could not have had significant water since then. The inner HZ radius is therefore reasonably well bracketed. The evolution of these inner HZ boundary radii for the Sun are shown in the bottom three curves of Figs. 1a and 1b.

Three critical fluxes corresponding to the outer radius of the HZ were also identified by Kasting et al. (1993). In normalized units these flux limits are 0.32, 0.36, and 0.53. The smallest and least conservative limit corresponds to the flux at early Mars 3.8 Gyr ago in the standard solar model. This limit is based on arguments (e.g., Pollack et al. 1987) that early Mars had a warm and wet climate and therefore must have been in the Sun's HZ. (Because of its low mass of 0.1 $M_\oplus$, Mars is not an Earth-like planet as we define it. An Earth-mass planet at the distance of Mars from the Sun might have maintained a stable climate for a much longer period.) The intermediate theoretical flux limit of 0.36 corresponds to the maximum possible CO_2 greenhouse heating, which occurs for a CO_2 partial pressure of ~8 bar (Kasting et al. 1993; Kasting 1991; Whitmire and Reynolds 1996). At higher CO_2 partial pressures, the increase in planetary albedo outweighs the increase in greenhouse heating. Since the actual solar flux at Mars 3.8 Gyr ago was 0.32 in the standard model, there is a theoretical discrepancy between these two limits. This discrepancy is currently unresolved but might be explained by the presence of other greenhouse gases in Mars' early atmosphere (Kasting 1991; Sagan and Chyba 1997), by a scattering variant of the greenhouse effect (Forget and Pierrehumbert 1997), or by a nonstandard solar model in which the Sun's ZAMS mass was 4–7% greater than the present value (Graedel et al. 1991; Whitmire et al. 1995). Other possible astronomical explanations for an increase in the solar flux at early Mars have been discussed by Whitmire et. al. (1995).

The most conservative flux limit for the outer boundary is the "first condensation" limit of 0.53. This is the flux at which CO_2 first begins to condense and thus to increase the planetary albedo. This limit is probably too conservative but is difficult to improve on without a climate model that can treat CO_2 clouds. Kasting et al. (1993) used these three estimates of the critical minimum flux necessary to sustain a mean surface temperature of 273 K, along with a standard solar evolution model, to generate the evolution of the outer HZ boundary radii (three upper curves) in Figs. 1a and 1b.

These figures show the evolution of the Sun's HZ, i.e., the inner and outer radii versus time, for sets of the paired critical fluxes. The three sets are paired in the following way. Case 1 corresponds to the two most conservative flux limits, the moist greenhouse (1.1) and the first condensation point (0.53). Case 2 is the intermediate case and corresponds to limits determined by the runaway greenhouse (1.4) and the maximum greenhouse (0.36). Case 3 is our least conservative case and corresponds to limits inferred from the lack of water on Venus as of 1 Gyr ago (1.76) and the evidence for the presence of liquid water on early Mars (0.32).
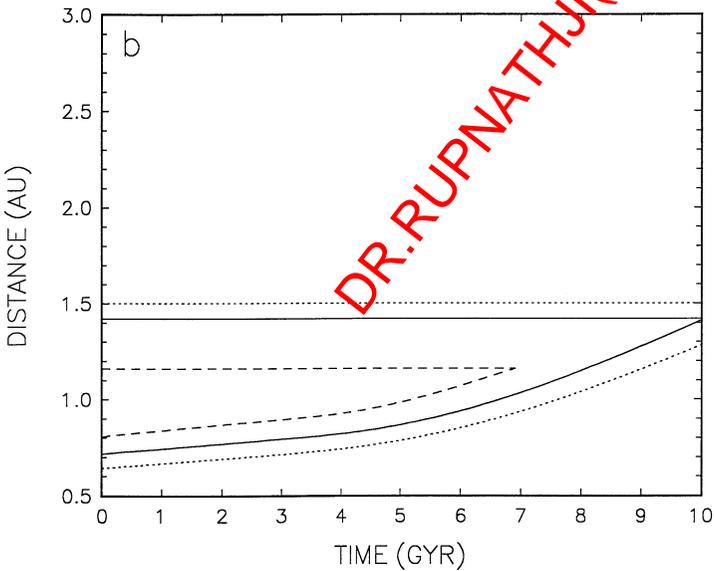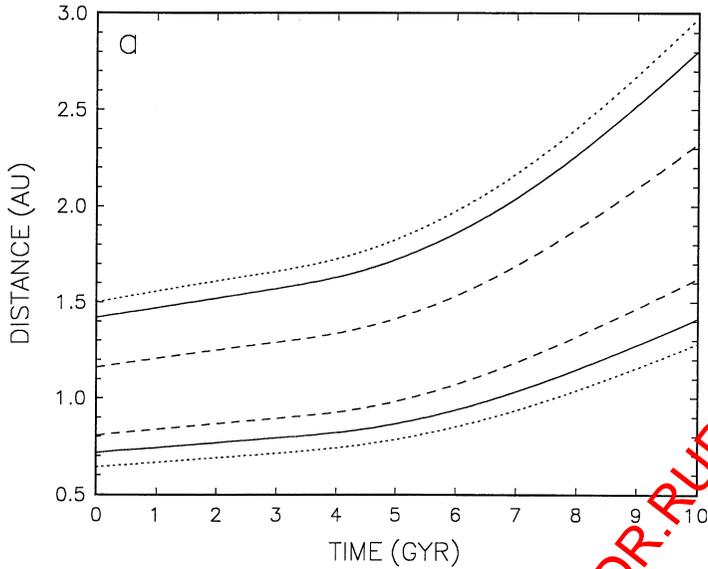
Figure 1. Evolution of the HZ around a 1-M$_\odot$ star for two different assumptions concerning the possibility of planetary "cold starts": (a) cold starts permitted; (b) no cold starts allowed. The term "cold start" refers to whether or not a planet that is initially beyond the outer edge of the HZ will deglaciate once the stellar luminosity increases to the appropriate critical value. The three pairs of curves correspond to the different habitability estimates discussed in the text: long dashes, "water loss" and "first CO$_2$ condensation" limits (most conservative); solid curves, "runaway" and "maximum greenhouse" limits; dotted curves, "recent Venus" and "early Mars" limits (most optimistic). (Figure from Kasting et al. 1993.)

The time evolution of the three HZ cases shown in Fig. 1a is based on the assumption that a planet initially beyond the outer boundary of the HZ and therefore frozen, will deglaciate once the solar flux reaches a value equal to the calculated climatic limits. On the other hand, Caldeira and Kasting (1992) have argued that a planet that formed beyond the outer boundary of the HZ would develop a reflective blanket of ice, reducing the absorption of solar radiation. Such a planet might also develop thick, highly reflective, CO_2 clouds (Kasting 1991). A planet that undergoes global glaciation soon after accretion might thereby remain in that state even when the solar flux increases beyond the appropriate (lower) critical value discussed above. Thus, it may be impossible to "cold start" an initially frozen planet before the solar flux increases by a factor of $\sqrt{2}$ and exceeds the critical greenhouse value (Caldeira and Kasting 1992).

However, recent evidence that the Earth may have completely glaciated during the Neoproterozic and subsequently deglaciated supports the view that "cold starts" are in fact possible (Hoffman et al. 1998). Moreover, Forget and Pierrehumbert (1997) have shown that the high-albedo properties of CO_2 clouds may be countered by an increased greenhouse effect due to the clouds' scattering of infrared radiation. It might also be possible that a major climatic perturbation, such as a massive impact or extensive volcanism, could "jump start" a frozen planet. Assuming that cold starts are possible, it can be seen from Fig. 1a that the HZ moves outward and becomes broader in time.

Figure 1b shows the same evolution as Fig. 1a but with the more conservative assumption that cold starts are not possible during the main-sequence phase. In this case the outer boundary of the HZ is constant and equal to its ZAMS value. The inner boundary radius moves outward in time as before, so the HZ now becomes narrower in time.

Continuously habitable zones for any assumed time period can be obtained from Figs. 1a and 1b for the three limiting cases. For our most conservative Case 1 fluxes without cold starts, the 4.5-Gyr CHZ extends from 0.95 to 1.15 AU, which is a factor of 5 larger than that found in earlier work (Hart 1979). For our least conservative Case 3, the 4.5-Gyr CHZ extends from 0.75 to 1.9 AU. For simplicity of discussion here and in the next section we shall focus on the intermediate Case 2. For this case the 4.5-Gyr CHZ extends from 0.84 to 1.77 AU if cold starts are possible, and from 0.84 to 1.43 AU if they are not.

C. Implications for SETI

Figure 1 has interesting implications for the Search for Extraterrestrial Intelligence (SETI). One long-standing objection to the prospects for intelligent life elsewhere (e.g., Mayr 1995) is the claim that the evolution of intelligence on Earth was an extraordinarily unlikely event, contingent on very special circumstances. If we could rewind the tape of life and start again from the beginning, this argument runs, nothing like human

intelligence would again evolve. Although the Earth has seen the multiple independent evolution of such highly selected capabilities as flight and sight, technical intelligence is argued not to be analogous to these. Metazoa arose on Earth over 550 Myr ago (Runnegar 1992), but technical intelligence has only just arisen for the first time, in only one of the billions to tens of billions of species that have existed on Earth.

One objection to this argument is that it seems unsurprising that the first intelligent species on a planet would look back over the history of life and ask why it, among all others, was first. But the objection (Chyba 1999) can be expressed more precisely with the help of Fig. 1. The total expanse of time over which metazoa are likely to exist on Earth is much greater than the ~600 Myr during which they have so far existed. Figure 1 shows that Earth will likely remain habitable for another ~2 Gyr, after which it will become uninhabitable due to the increasing luminosity of the Sun. Until that time it seems probable (not certain) that metazoa are here to stay: It would be a remarkable extinction indeed for every worm, every clam, every cockroach, and every rat to disappear (although the elimination of photosynthesis might accomplish this). Metazoa therefore seem likely to endure *in toto* for over 2.5 Gyr of Earth history. From this perspective, technical intelligence arose on Earth *early* in the history of metazoa, and it is less clear that we should be impressed by the observation that, from our point of view, technical intelligence is a latecomer on the scene. Such an argument appears strongly rooted in the contemporary human perspective. Nevertheless, none of these arguments seems likely to be compelling in the absence of additional data, arguing that SETI remains fundamentally a problem for empirical investigation.

D. Evolution of the Habitable Zone around Other Stars

The same type of HZ calculations can be performed for stars with masses different from the Sun's. Main-sequence stars much more massive than the Sun have large HZs on an absolute scale, but their lifetimes are arguably too short to be of interest as sites for the evolution of complex organisms (Huang 1960; but see McKay 1996). For the massive O-type stars it is doubtful whether there is even sufficient time for planets to form during their $\sim 10^6$-yr stellar lifetimes (Bodenheimer 1989). The main-sequence lifetime of a star, τ_{ms}, is proportional to M/L. Since $L \propto M^{4.75}$ over the mass range of most interest (Iben 1967), $\tau_{ms} \propto M^{-3.75}$. Here we restrict ourselves to stellar lifetimes greater than 2 Gyr, which correspond to masses less than 1.5 $M_\odot$. At the other extreme, the low-mass main-sequence M stars with masses ≤ 0.5 $M_\odot$ have lifetimes longer than the age of the universe. Their evolution in 10 Gyr is negligible, so their 4.5-Gyr CHZ is identical to their ZAMS HZ.

Figures 2a and 2b show the evolution of the HZ (for Case 2 fluxes) around stars of selected masses between 0.5 and 1.5 $M_\odot$, with and without cold starts, respectively. The effect of stellar temperature on the black-body spectrum of light and, hence, on planetary albedo has been taken

into account. The fluxes were corrected for stellar temperature. Details of this modeling may be found in Kasting et al. (1993). For the stars in Fig. 2, the widths of various CHZs can be obtained for any assumed relevant timescale. Assuming no cold starts, the CHZ for a given τ is equal to the HZ at time $t = \tau$.

IV. ACCRETION OF PLANETS IN THE HABITABLE ZONE

A. Accretion of Planets in the Habitable Zone of Single Stars

Wetherill (1996) numerically investigated the problem of accretion of terrestrial planets around stars of masses between 0.5 and 1.5 $M_\odot$ and found that, for circumstellar disk parameters that are not too different from those of the solar system, the number and radial distribution of final terrestrial planets are insensitive to stellar mass and that these planets concentrate in the vicinity of 1 AU. However, the location of the HZ is quite sensitive to stellar mass; it lies inside the 1-AU planet formation region for low-mass stars and beyond the terrestrial planet formation region for high-mass stars. That is, terrestrial planets would be too cold around low-mass stars and too hot around high-mass stars. In the case of 1-$M_\odot$ stars there was nearly always a planet of mass $\geq \frac{1}{3}$ $M_\oplus$ formed in the HZ. In addition to the assumption of circumstellar disk parameters similar to those of the solar system, these simulations also assumed the existence of Jupiter-like planets. In the absence of jovian planets, the median terrestrial planetary mass was 2 $M_\oplus$ for the same initial surface density used in the models characteristic of the solar system.

The fundamental assumption of that study, namely, an initial circumstellar accretion disk similar to those used in modeling the solar system, may not be generally valid. For example, the disk mass distribution may scale with stellar mass (Kasting et al. 1993; Whitmire and Reynolds 1996) in such a manner that terrestrial planets form closer than 1 AU around low-mass stars and farther than 1 AU around high-mass stars, making it more likely that planets would form in the HZ. Kasting et al. (1993) gave arguments suggesting that planet formation distances should scale with stellar mass. If it is further assumed that planet spacing is generally logarithmic (i.e., equal numbers of planets in each decade of semimajor axis), as is true in the solar system and the jovian system and as found in various numerical studies (Isaacman and Sagan 1977; Lissauer 1995; Wetherill 1996), Whitmire and Reynolds (1996) showed that the number of planets in the HZ would be independent of stellar mass. If this conclusion is correct, most habitable planets in the galaxy would reside around K and high-mass M stars.

However, one important uncertainty in these results is our need to understand the origin of "hot Jupiters" (Marcy and Butler 1998), Jupiter-mass planets well within 1 AU of their stars. If these objects arise as a result of one or another type of planetary migration (Weidenschilling and Marzari 1996; Murray et al. 1998; Trilling et al. 1998), the implications of
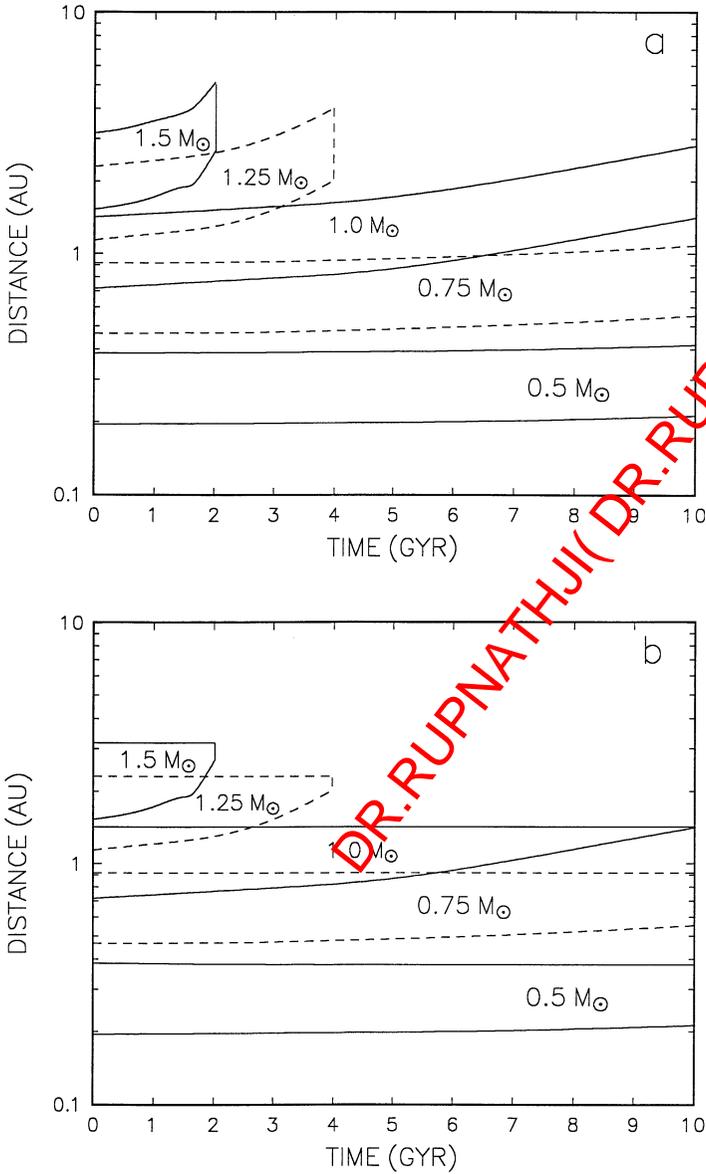
Figure 2.   Evolution of the HZ around stars of different masses for two assump-
tions about the possibility of planetary cold starts: (a) cold starts permitted; (b)
no cold starts allowed. The intermediate (runaway and maximum greenhouse)
estimates for the width of the HZ were used, and the evolution was truncated at
the end of the main-sequence phase. (Figure from Kasting et al. 1993.)

these migrations for the formation of terrestrial planets in the HZ are an important concern that needs to be understood.

B. Accretion of Planets in the Habitable Zone of Binary Star Systems

Whitmire et al. (1998) numerically studied terrestrial planet formation in the HZs of binary star systems. Assuming current models of terrestrial planet formation in the solar system, they investigated the conditions under which the secondary star would inhibit planet growth in the HZ. Runaway accretion was assumed to be precluded (i) if the secondary caused the planetesimal orbits to cross within the runaway accretion timescale and (ii) if, during crossing, the relative velocities of the planetesimals were accelerated beyond a certain critical value that results in disruptive collisions rather than accretion. For a two-solar-mass binary with planetesimals in circular orbits about one star at 1 AU, and a typical wide binary eccentricity of 0.5, the minimum binary semimajor axis a_c that would not inhibit planet formation is 32 AU. Similar results were presented for a range of binary eccentricities e_B, secondary masses m, critical disruption velocities U_c, and mean planetesimal locations $\bar{a}$. A semiempirical relation between these parameters and the critical semimajor axis was found to be

$$a_c = 16(1 - e_B)^{-1}(m/1\ \text{M}_\odot)^{0.31}(\bar{a}/1\ \text{AU})^{0.80}(100\ \text{m s}^{-1}/U_c)^{0.30}\ \text{AU}$$

For fixed m the e_B dependency corresponds to a constant periastron distance. For two 1-$\text{M}_\odot$ stars this constant is 16 AU. Based on the distributions of orbital elements of a bias-corrected sample of nearby G dwarfs (Duquennoy and Mayor 1991), it was found that at least 60% of solar-type binaries cannot be excluded, *solely* on the basis of the perturbative effect of the secondary star, from having a habitable planet.

Whitmire et al. (1998) found that 12 of 18 systems containing newly discovered giant extrasolar planets or brown dwarfs can be excluded from having a habitable planet at 1 AU, *assuming* the secondaries formed *in situ* in their present orbits. If they formed further than 1 AU from the star and then migrated or were scattered inward, a greater fraction of these systems might be excluded. We note however that only ~5% of observed stars have giant planets or brown dwarfs within detectable (less than ~3 AU) limits (Marcy and Butler 1998).

V. HABITABILITY OF WORLDS WITHIN THE HABITABLE ZONE

A. Planetary Obliquities

The Earth's obliquity would vary chaotically from 0 to 85 degrees were it not for the presence of the Moon (Laskar and Robutel 1993; Laskar et al.

1993). The Moon is believed to have formed as the result of a stochastic glancing collision with a Mars-sized embryo. This type of collision may be uncommon in the planet formation process. The fact that Earth is the only terrestrial planet with a major moon lends support to this idea. Noting the likely extreme climatic fluctuations that would occur on planets with high obliquities, Laskar et al. (1993) suggested that habitable planets may be rare. We note that the large chaotic variation of the Earth's spin axis is due to the presence of the other planets, primarily Jupiter, as well as Earth's planetary quadrupole moment.

To test the assertion that extreme obliquities would lead to climatic variations that would make a planet uninhabitable, Williams and Kasting (1997) used an energy balance climate model to simulate the Earth's climate at obliquities up to 90 degrees. They found that Earth's climate would become regionally severe, with large seasonal cycles and accompanying temperature extremes on middle- and high-latitude continents, which might be detrimental to some forms of life. Whether such variations would pose a problem for the origin of life or for microbial life seems less likely (Chyba 1996b). The response of other, hypothetical, Earth-like planets to large obliquity fluctuations depends on their land-sea distribution and on their position within the HZ. Planets with several modest-sized continents or equatorial supercontinents are more climatically stable than those with polar supercontinents. Planets farther out in the HZ are less affected by high obliquities because their atmospheres should accumulate CO_2 in response to the carbonate-silicate cycle. Dense CO_2 atmospheres transport heat very effectively and therefore limit the magnitude of both seasonal cycles and latitudinal temperature gradients. Therefore, a significant fraction of extrasolar Earth-like planets may still be habitable, even if they were subject to large obliquity fluctuations.

B. Synchronously Rotating Planets

Dole (1964) noted that habitable planets around M dwarfs are likely to be synchronously rotating, with one hemisphere always illuminated by the parent star and the other hemisphere in perpetual darkness. Planets in the HZ of late K dwarfs can also be synchronously rotating (Kasting et al. 1993). The M dwarfs are believed to be the most numerous ($\sim$75%) of stars, having masses in the range 0.1–0.5 $M_\odot$ (Rodonò 1986). [However, recent observations indicate that M stars in the mass range 0.1–0.3 $M_\odot$ are more than an order of magnitude less abundant than previously believed (Gould et al. 1997).] If the atmosphere of a synchronously rotating planet is in radiative-convective equilibrium, the surface temperature on the dayside will be very high, while the nightside will be so cold that the major atmospheric constituent will condense out on the surface.

Joshi et al. (1997) used a three-dimensional climate model to investigate the conditions under which atmospheric collapse would occur on synchronously rotating planets in the HZ. They find that if CO_2 partial pressure is controlled by the carbon-silicate cycle, these planets would

need a minimum surface pressure of 1–1.5 bar of CO_2 in order to support liquid water on the dark hemisphere. The minimum pressure necessary to prevent atmosphere collapse is $\sim$30 mbar. Thus, they conclude that synchronously rotating planets in the HZ of M stars could support atmospheres over a large range of conditions, and even surface liquid water under certain conditions.

C. Habitable Moons around Extrasolar Giant Planets

The jovian-mass planet around the solar-type star 16 Cygni B has an elliptical orbit that lies in the HZ part of the time. The star 47 Ursae Majoris has a jovian-mass planet in a circular orbit that lies near the least conservative outer limit of the HZ. It seems likely that these jovian planets are themselves not habitable (Chyba 1997); however, they may have large habitable moons. Williams et al. (1997) have investigated constraints on the habitability of such moons and find that a rocky moon orbiting jovian planets or brown dwarfs lying in the stellar HZ could be habitable provided that (1) the moon's mass is $\geq$0.12 $M_\oplus$, in order to retain a substantial and long-lived atmosphere, and (2) the moon has a Ganymede-like magnetic field sufficient to prevent the atmosphere from being sputtered away by the bombardment of energetic ions from the planet's magnetosphere. Long-term habitability requires the operation of the carbonate-silicate cycle and therefore some form of geological activity. If driven by radiogenic heating, a minimum mass of 0.23 $M_\oplus$ is required. If the moon is in an Io-like orbit in resonance with another more distant moon, then tidal heating could supply the internal heat source necessary to drive plate tectonics or other geological activity and thus maintain surface liquid water for Gyr timescales.

VI. CONCLUSIONS: AN EXPANDING ARENA FOR LIFE

As a practical matter, at least for the present, the search for extraterrestrial life is the search for life as we know it, life made of organic molecules in liquid water. Since organics are common in much of the solar system (Cruikshank 1997) and in interstellar space (Pendleton and Chiar 1997), liquid water has become the focus of exobiological searches.

It has become clear in recent years that there is a deep subsurface biosphere on Earth (Gold 1992; Whitman et al. 1998). It is still an open question whether life may in fact have originated in the subsurface. Therefore, deep liquid water environments, such as we now suspect may exist on Mars and Europa, could be plausible locales for extraterrestrial life in our own solar system or elsewhere.

The most conservative and observationally relevant requirement to set for extraterrestrial habitable environments is not to require liquid water at depth, but at a world's surface. Assuming this, the "circumstellar habitable zone" is defined as the volume of space around a star (or star

system) within which an Earth-like planet could support surface liquid water. Although these zones change with evolving stellar luminosity, there are significant habitable zones lasting for billions of years around stars with masses between 0.1 and 1.5 times the mass of the Sun. Even a conservative definition of habitability suggests abundant locales for life around other stars.

The detection of oxygen and water in the spectrum of a terrestrial planet lying in a star's habitable zone could provide important remote evidence of life (Woolf and Angel 1998). The presence of methane, simultaneously with oxygen and water, would be even more suggestive. However, it should be cautioned that both Ganymede and Europa show spectroscopic evidence for molecular oxygen (Spencer et al. 1995; Hall et al. 1995). Indeed, Europa has a tenuous O_2 atmosphere (Hall et al. 1995), thought to be produced by the sputtering of ice by energetic particles from the jovian magnetosphere (Sieger et al. 1998). One lesson of the *Viking* missions to Mars is that anticipated unambiguous signatures of biology may prove to be less certain in the face of unanticipated nonbiological processes.

Nonetheless, it is exciting that the detection of spectroscopic signatures highly suggestive of life on nearby extrasolar planets is within the capabilities of existing or foreseeable technology (Woolf and Angel 1998). Such measurements have been proposed using a system of orbiting IR telescopes operating as an interferometer. Ongoing SETI searches offer an important complementary approach in the search for extraterrestrial life (Tarter and Michaud 1990; Dick 1996; Tarter 1997). While our knowledge remains too limited to assess quantitatively the likelihood of finding extraterrestrial biology, the combination of new discoveries about Earth's deep biosphere, the apparent subsurface liquid water environments elsewhere in our solar system, the theoretical recognition that circumstellar habitable zones are more expansive than once thought, and the discovery of extrasolar planets all combine to make the next decades the most exobiologically promising in the history of astronomy.

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