First published online as a Review in Advance on May 2, 2005

ASTROBIOLOGY: The Study of the Living Universe

Christopher F. Chyba and Kevin P. Hand

*SETI Institute, Mountain View, California 94043 and Department of Geological and
Environmental Sciences, Stanford University, Stanford, California 94305;
email: chyba@seti.org, khand@stanford.edu*

Key Words   bioastronomy, cosmobiology, exobiology, SETI

■ **Abstract**   Astrobiology is the study of the living universe. Astronomy provides the
context for the origin and evolution of life on Earth. Conversely, discoveries about the
terrestrial biosphere—from extremophilic microbes to the evolution of intelligence—
inform our thinking about prospects for life elsewhere. Astrobiology includes the search
for extraterrestrial life via in situ exploration, spectroscopy of solar and extrasolar plan-
etary atmospheres, and the search for extraterrestrial intelligence. This review situates
astrobiology within philosophical issues of the definition of life and the biological
compatibility of the universe. It reviews the habitability of the Galaxy in general and
of planets and moons in particular, and summarizes current controversies in origins-
of-life research and in evidence for the earliest life on Earth. It critiques certain "rare
Earth" and "anthropic" arguments, and considers four approaches to deciding whether
intelligent life exists elsewhere in the Galaxy. It concludes that astrobiology must also
speak to the future of human civilization.

1. THE SCIENCE OF ASTROBIOLOGY

The NASA Astrobiology Institute (NAI) defines astrobiology as "the study of
the living universe" (NAI 2004). Implicit in this definition is that astrobiology
includes the study of terrestrial biology. This is appropriate, for our approach to
the search for life elsewhere is influenced by our knowledge of life on Earth, and our
understanding of the origin and evolution of life on Earth is informed by our study
of conditions on other worlds and of Earth's solar system and galactic environment.
In this respect astrobiology is now understood more broadly than when the term
was first coined, apparently by Laurence Lafleur (1941), who defined it as "the
consideration of life in the universe elsewhere than on earth."

The word astrobiology was used by the astronomer Otto Struve (1955), and
was adopted by NASA in 1995 (NAI 2004). Prior to that, the word exobiology
was most commonly used in U.S. space exploration. The term exobiology dates to
an agenda-setting paper by the biologist Joshua Lederberg (1960), and the word is
still used occasionally within NASA and, more commonly, by the European Space
Agency (ESA). "Astrobiology" avoids the combination of Greek and Latin roots
in "exobiology," but has the drawback of seeming to imply that one is somehow

studying the biology of stars (*astron* is from the Greek for star), so seems a less appropriate combination than its cousin words astrophysics or even astrochemistry. The word cosmobiology (for the biology of the cosmos), employed by the physicist J.D. Bernal (1952; Dick 1996), may in fact be the best choice but is currently seldom used. Finally, the term bioastronomy is used by the International Astronomical Union (IAU 2004) but is rarely heard outside the meetings and proceedings of that body. We treat the words as synonyms of comparable intellectual pedigree, but in keeping with current U.S. practice, adopt astrobiology unless a historical point requires a different choice.

The science of exobiology was famously criticized by the biologist George Gaylord Simpson (1964), "in view of the fact that this 'science' has yet to demonstrate that its subject matter exists!" Earlier, Struve (1955) had concluded that the time was "probably not yet ripe" to recognize a new astronomical discipline by this name. If exobiology (or astrobiology) were understood to mean solely the study of extraterrestrial life—which it is not—Simpson's criticism would remain strictly true but might nevertheless seem bizarre to many astronomers or physicists. Astrophysicists, after all, spent decades studying and searching for black holes before accumulating today's compelling evidence that they exist (Melia & Falcke 2001). The same can be said for the search for room-temperature superconductors, proton decay, violations of special relativity, or for that matter the Higgs boson. Indeed, much of the most important and exciting research in astronomy and physics is concerned exactly with the study of objects or phenomena whose existence has not been demonstrated—and that may, in fact, turn out not to exist. In this sense astrobiology merely confronts what is a familiar, even commonplace situation in many of its sister sciences.

2. WHAT IS LIFE?

If astrobiology is the study of the living universe, it is important to inquire into what we mean by the word living. "What is life?" Erwin Schrödinger (1945) famously asked, and in doing so he was returning to a question that was asked at least as long ago as Aristotle (*De Anima*, 415[a22]–415[b2]). To this day, there is no generally accepted definition of the word. Carl Sagan (1970) catalogued a list of failed attempts, including physiological, metabolic, biochemical, genetic, and thermodynamic definitions, and there have been other attempts as well [for only a few among many more recent discussions, see Feinberg & Shapiro (1980), Joyce (1994), Koshland (2002), and Schulze-Makuch & Irwin (2004)[1]]. All the proposed definitions face problems, often in the form of robust counter-examples

---

[1]Oddly, Schulze-Makuch & Irwin (2004) state (p. 13) that Chyba & McDonald (1995) "postulated that life is a system that acquires nutrients from its environment, responds to stimuli, and reproduces." In fact, nowhere did Chyba & McDonald (1995) postulate this, nor is it their point of view.

(Chyba & McDonald 1995); for example, metabolic definitions of life find it hard to exclude fire (which grows and even reproduces through chemical reactions that are essentially the same as those used by some organisms), and thermodynamic definitions find it hard to exclude mineral crystals (which create and sustain local order, and may also reproduce).

Yet the philosophical question of the definition of life has increasing practical significance. The utility of an agreed definition grows as science progresses toward understanding the origin of life on Earth, as laboratory experiments approach the synthesis of artificial life as measured by the criteria of some definitions, and as the search for life on Mars or Europa becomes the driver for a succession of planetary missions. The design of life-detection experiments on spacecraft make explicit or implicit assumptions about what life is, and what measurements will be sufficient to demonstrate its presence or absence.

For example, the biology package experiments on the Viking spacecraft landers all searched for signs of microbial metabolism. One of these experiments, the Labeled Release experiment, gave results that were described by the head of the Viking biology team as data that "would almost certainly have been interpreted as presumptive evidence of biology" had "information from other experiments on board the two Viking landers. . . not been available" (Klein 1978). Most important among these was the failure of the Viking gas chromatograph mass spectrometer (GCMS) to find organic molecules to its limits of detection with stepwise heating of martian soil samples up to 500°C (Biemann et al. 1977). Although it now appears that the implications of these results for the absence of martian microbes may be weaker than they initially seemed (Benner et al. 2000, Glavin et al. 2001), at the time the conclusion seemed powerful: no organic molecules means no life. In effect, a search that implicitly applied a biochemical definition trumped a search that applied a metabolic definition (Chyba, Whitmire & Reynolds 2000).

Chyba and the philosopher Carol Cleland have drawn on philosophical investigations into language and definition to explain why defining life has proven so intractable. They argue that the idea that one can answer the question "what is life?" by defining life is mistaken, resting on confusions about the nature of definition and its ability to answer fundamental questions about the natural world (Cleland & Chyba 2002, 2005). Rather, to answer the question "what is life?" we require not a definition but a scientific theory, analogous to the theory of molecules that permits one to give an unambiguous answer to the question "what is water?" Prior to molecular theory, the best a scientist could do in defining water would be to define it in terms of its sensible properties, such as its being a transparent, odorless, and tasteless liquid. Yet even these properties may seem ambiguous or inconstant, and indeed, this was the dilemma Leonardo da Vinci (1513) faced when trying to give an account of the nature of water. But centuries later, once there was a good general theory of atoms and molecules, water could be unambiguously identified as H_2O. A precise answer to the question "what is water?" is possible only when situated within an appropriate scientific theory. Similarly, in the absence of a general theory of the nature of living systems (which may or may not prove possible), neither

analysis of the features that we currently associate with life nor attempts to postulate a definition for it are likely to yield a particularly informative answer to the question "what is life?" For the time being, astrobiologists, like other biologists, are in a position analogous to that of Leonardo in trying to make sense of the seemingly changing nature of water before anyone understood hydrogen, oxygen, or atomic bonds.

3. "LIFE AS WE KNOW IT"

There are currently three ways that scientists search for extraterrestrial life: (*a*) in situ (and ultimately, sample return) searches within the solar system; (*b*) the spectral examination of planetary (and soon, extrasolar planetary) atmospheres for chemical evidence of life; and (*c*) searches for evidence of extraterrestrial technology. Ideally, these investigations would be conducted in the context of an agreed and precise understanding of the nature of life, yet as we have just seen, such an account is, for fundamental reasons, not available.

For this reason, searches for life within our solar system commonly retreat from a search for life to a search for "life as we know it," meaning life based on liquid water, a suite of so-called "biogenic" elements (most famously carbon), and a usable source of free energy. Because carbon-based molecules and useful sources of energy are common (though not ubiquitous) throughout the solar system, whereas for some time it appeared that liquid water might prove to be quite rare off of the Earth, the search for life in the solar system came to emphasize the search for liquid water. Life on Earth appears to have an absolute requirement for liquid water (Mazur 1980, Horowitz 1986). This requirement is reflected, for example, in the slogan "follow the water," adopted by NASA's Mars exploration program (NASA JPL 2004) as its strategy for answering what it calls the "defining question for Mars exploration" of whether there is life on Mars.

Life is dependent on liquid water because it requires an internal medium within which molecules may dissolve and chemical reactions may occur. Indeed, 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, and it may be possible to construct biomolecules with ammonia as their solvent (Haldane 1954). However, at one atmosphere pressure most polar solvents, including ammonia, are stable liquids only at much colder temperatures than water (Barrow & Tipler 1986). A biochemistry employing liquid ammonia at atmospheric pressure would proceed far more slowly than terrestrial biochemistry because of the typical Arrhenius exponential dependence of chemical reaction rates with temperature. But it should be sufficient for a biochemistry to catalyze reactions substantially faster than they occur in the environment—relative rates are more important than absolute rates, provided extrinsic environmental factors do not intervene. Moreover, at extremely high pressures such as those obtained in jovian planets, ammonia could remain liquid up to its critical temperature of 132°C (Schulze-Makuch & Irwin 2004).

One is also free to imagine an exotic biology whose solvent would be a non-polar liquid, in this sense just the opposite of that for life on Earth. Such speculations (Benner, Ricardo & Carrigan 2004; Schulze-Makuch & Irwin 2004) are poorly constrained because any such biochemistry would be so different from that of terrestrial life. However, the elucidation of the organic chemistry of Saturn's moon Titan will shed light on these possibilities. Surface conditions on Titan permit the nonpolar molecules methane (CH_4) and ethane (C_2H_6) to exist as liquids (Lunine, Stevenson & Yung 1983), and Titan appears to have a meteorological cycle based on methane (Griffith, Hall & Geballe 2000). Moreover, photo- and charged particle-chemistry of CH_4 in Titan's atmosphere drive the production of copious organics in Titan's atmosphere (Sagan, Thompson & Khare 1992). The exploration of Titan, and in particular the chemical analyses by the Huygens probe (ESA 2005a), may shed light on the plausibility of nonpolar solvents as the basis for an alternative nonpolar biology.

One could also relax the requirements for life as we know it by considering the prospects for life based on an atom other than carbon. Silicon is the commonly suggested alternative, as it underlies carbon on the periodic table, so should have similar chemical properties, and it is also cosmically abundant (Feinberg & Shapiro 1980). However, silicon does not readily form double bonds as does carbon, because its larger atomic size reduces the volume of the necessary p-orbital overlap (Huheey, Keiter & Keiter 1993). The result is that silicon-based chemistry is much less flexible than that based on carbon. Indeed, approaching a hundred carbon-based (mostly organic[2]) molecules have been identified in the interstellar medium (Ehrenfreund et al. 2002), whereas no comparable suite of varied silicon-based molecules has been found. Our growing empirical knowledge of the chemistry of the Galaxy suggests that a complex carbon-based chemistry may be common, but that this is not the case for silicon. Carbon therefore appears to be the more likely basis for life elsewhere.

As far as is known, life on Earth obtains its energy in one of two ways. Either it captures light, or it uses chemical energy—either by respiration [combining a fuel (an electron donor) with an oxidant (an electron acceptor)], or through fermentation (in which organics serve as both the primary electron donor and ultimate electron acceptor). There is now known to be an impressive array of compounds, mostly not organic, that microscopic organisms use as fuels, and a comparable number, mostly not involving molecular oxygen, that microscopic organisms use as oxidants (Nealson 1997). In extraterrestrial environments where sunlight is not readily available (such as in the ice-covered ocean of Jupiter's moon Europa), biological speculation focuses on ways independent of sunlight to produce biologically useful electron donors and acceptors (Chyba & Hand 2001). Less analogously to life on Earth, speculation for alternative biological sources of energy may encompass the capture of energy from electromagnetic fields, kinetic energy, gravity, or other sources (Schulze-Makuch & Irwin 2004).

---

[2]Organic molecules are molecules based on carbon that contain hydrogen or nitrogen and possibly other atoms.

Because of the liquid water requirement of terrestrial life, the search for life in our solar system has focused on those objects where liquid water may now exist, or may once have existed: Mars (Kargel 2004) and Europa, as well as other large icy satellites that may harbor subsurface oceans (Chyba & Phillips 2005), and the possibly once-liquid deep interiors of large asteroids (Chyba & McDonald 1995) and comets (Podolak & Prialnik 1997). The exception is Titan, though even in this case most speculation about Earth-like prebiotic chemistry has focused on impact-driven transient liquid water environments (Thompson & Sagan 1992).

4. A UNIVERSE COMPATIBLE WITH LIFE

Extraterrestrial biology appears possible because the universe beyond Earth is similar in important respects to the universe of our direct experience on Earth. This was not always held to be the case; in particular, Aristotle (*De Caelo*) posited a radical dichotomy between the heavens and the Earth. His reasoning was based on observation: objects in the terrestrial realm naturally move in straight lines, either toward or away from the center of the universe. Of the four elements of which Aristotle held terrestrial matter to be composed, earth and water naturally move toward the center (downwards), whereas air and fire move away from the center (upwards). This in turn implies that the Earth must be spherical (consistent with observation) and centered on the center of the universe. Objects in the heavens, however, clearly move in circles about the Earth, i.e., about the center of the universe. They therefore obviously obey a different physical law—circular (and therefore eternal) motion, rather than linear. That in turn must mean that they are not made of the four terrestrial elements, but rather of a fifth element, the quintessence. The heavens therefore both obey different physical laws and are made of entirely different stuff than is the case for the objects of our daily experience on Earth. Had this view of the universe turned out to be correct, astrobiology would be simply impossible, obviously mistaken.

Although there were rival cosmologies to those of Aristotle, even in the Greek world (Dreyer 1953), it was not until Newton (with anticipation by Descartes and Hooke) that it was demonstrated that the same laws of physics apply to the heavens as well as the Earth (Kuhn 1957). In Book III of *The Principia*, Newton (1686) demonstrated that the same inverse-square law of gravitation that explained the acceleration of falling objects and projectile motion on Earth also explained the elliptical motion of planets around the Sun, or that of moons around planets. The same universal law applied to the terrestrial and heavenly realms, ending the Aristotelian dichotomy.

The development of spectroscopy and its subsequent placement on a firm scientific basis by quantum mechanics in the early twentieth century allowed Payne-Gaposchkin (Payne 1925) to demonstrate in her PhD thesis the chemical homogeneity of the stars and their similarity to Earth, apart from large differences in hydrogen and helium abundance. The heavens therefore not only obey the same laws as on Earth, but they are made of the same material—a demonstration that largely completed the overthrow of Aristotelianism begun by Copernicus (1543).

In this context there is some irony in the recent determination that matter like that we know on Earth in fact comprises only some four percent of the mass-energy of the universe (Hu & Dodelson 2002). Most of the stuff of the cosmos is in fact different from what we know on Earth, and even gravity may seem to behave differently on cosmic scales than on the terrestrial (Carroll 2001). There is therefore a whiff of Aristotelianism in recent cosmological discoveries, but this does not change the fact that we live in a universe that appears compatible with life over vast stretches of space and time. Whether the Copernican program will be extended into the biological realm and it will be discovered that we live in a "biological universe" (Dick 1996) or, at the other extreme, whether life will turn out to be unique to Earth, remains a question for empirical investigation. But there is nothing now known that rigorously excludes either possibility.

If the triumph of the Newtonian worldview made the universe safe for astrobiology, the triumph of big-bang cosmology (Weinberg 1983, Bennett 2005; but see Narlikar & Padmanabhan 2001) requires that universe to have provided at least one origin of life. It once seemed possible that a steady-state model would provide an accurate description of the universe (Bondi & Gold 1948, Hoyle 1948). Had a steady-state model turned out to be correct, astrobiology would not be challenged but there would be no intellectual requirement to explain the origin of life, now viewed as one of astrobiology's great questions. For if the universe were infinitely old, life could be infinitely old, and no origin would need to be posited. With the triumph of big-bang cosmology and its finite age for the universe approaching fourteen billion years, however, the origin of life becomes a scientific puzzle that cannot be ducked. In the steady-state picture, the finite age of individual solar systems would still require the presence of life in individual solar systems to be explained. Life could be envisioned as originating in such systems, but alternatively it could be posited to arrive at them by drifting through space from other, older systems. The hypothesis of interstellar microbial transfer (Arrhenius 1903), more quaintly known as "panspermia," may therefore play a more fundamental role in a steady-state than in a big-bang universe. But because the universe had an origin, life must have had an origin, whether or not interstellar microbial transfer (Davies 1988) also occurs.

Despite our lack of scientific understanding of the origin of life, it is clear that the universe appears remarkably "fine-tuned" for life as we know it (Henderson 1913, Blum 1962, Carter 1974, Leslie 1996). The so-called anthropic principle (Carter 1974, Barrow & Tipler 1986) is sometimes invoked to illuminate this remarkable fact. In the literature to date, over thirty different anthropic principles have been promulgated, leading to what one philosopher has called the "anthropic hodepodge" (Bostrom 2002). The principle's "strong" version (Carter 1974) states that "the Universe (and hence the fundamental parameters on which it depends) must be such as to admit the creation of observers within it at some stage." This arguably tautologous statement (Leslie 1996) is useful if it reminds us that in our current position of occupying the only locale in the universe known to harbor life (and, a fortiori, intelligent life), we are subject to severe observation selection effects. The anthropic principle in this view is a statement of observer bias. In

particular, because of this selection effect we cannot validly apply the Coperni-can principle (the assumption that Earth occupies no privileged place in the universe) to conclude either that other life or other intelligent life exists. Nevertheless, some aspects of Copernican reasoning regarding intelligent observers may remain valid (Gott 1993), though this is a rich and widely controversial field (Bostrom 2002).

Responses to the fine-tuning puzzle often fall into two categories. The "design hypothesis" accounts for fine-tuning on the basis of purposeful design (Swineburne 1990, Gonzalez & Richards 2004). The "ensemble hypothesis" holds that the observable universe is only a small part of the totality of existence (Bostrom 2002), which as a whole is not fine-tuned. The latter explanation now appears a consequence of cosmology, with the idea that our universe (so our big bang) is but one episode, a kind of bubble in a "multiverse," which gives rise to an extremely large number of universes with different values of physical constants and different cosmic histories (Linde 1986, 1990; Leslie 1996; Rees 2001). In this picture, there is nothing surprising about finding ourselves within one of the large number of universes (which nevertheless may represent a tiny fraction of the total) in which conditions permissive of the evolution of intelligence hold.

5. THE GALACTIC HABITABLE ZONE

The laws and physical constant values of the universe may be compatible with intelligent life, but it could still be that many venues potentially habitable by complex life have turned out not to be so. The idea that there is a "belt of life" in the Galaxy, an annulus within which intelligent life is most likely to be found, was introduced by Marochnik & Mukhin (1986) in 1981, then expanded by Balázs (1986, 1988). Gonzalez, Brownlee & Ward (2001) named this belt the galactic habitable zone (GHZ), outside of which complex life would be unlikely to have a chance to evolve. Key parameters in defining the zone include metallicity, the nearby frequency of supernovae, and stellar age.

The metallicity of a parent star is an important factor in determining whether solar system formation occurs (Trimble 1995; Fischer, Valenti & Marcy 2004). In a spectroscopic analysis of over 80 stars so far known to host planets, Santos et al. (2003) find that the average metallicity is 0.24 dex greater than that of dwarf stars in the solar neighborhood, i.e., the Fe/H abundance is nearly twice as high in the planet-hosting stars.[3] After removing observational bias, they find that the probability of finding a $<18\ M_{\rm Jup}$ planet increases with metallicity. Stars with solar metallicity were found to have planets less than 1% of the time, whereas stars with [Fe/H] between 0.3 and 0.4 dex were found to have planets at least 7% of the

---

[3]Typically in these discussions the term metallicity is used to refer to [Fe/H], measured in units of dex. In general, $[A/X] \equiv \log_{10}(N_A/N_X) - \log_{10}(N_A/N_X)_{\odot}$, where N_A and N_X represent the number density abundance of elements A and X. Positive dex therefore means metallicity higher than that of the Sun.

time. No variation in this frequency distribution was found when planets of mass $20\,M_{\mathrm{Jup}} > M > 10\,M_{\mathrm{Jup}}$ were compared to those of mass $<10\,M_{\mathrm{Jup}}$ and no change was found when comparing single planet systems to multiple planet systems or when considering planets in binary systems.

Fischer, Valenti & Marcy (2004) examined the metallicity of 754 well-observed stars and found a very strong correlation between [Fe/H] and Doppler-detected extrasolar planetary systems. They report that 5–10% of stars of solar metallicity harbor planets, whereas at [Fe/H] $= +0.5$ (roughly three times the metal abundance of the Sun) this percentage rises to almost 20%. At low metallicity, [Fe/H] $=$ –0.5, the population of planets falls to a few percent.

As the density of stars increases toward the center of the galaxy, so too does the stellar metallicity. Therefore it would appear that planet formation, hence solar system habitability, should increase with decreasing galactic radius—all else being equal. But of course, there is more to the story.

Supernovae may have a severe effect on habitable planets within $\sim$10 parsecs of the event (Shklovskii & Sagan 1966; Clark, McCrea & Stephenson 1977). The total energy outburst from a Type II supernovae (stellar mass $> 10\,\mathrm{M}_{\odot}$) is $\sim 10^{52}$ erg (Colgate 1968) and the initial flash might destroy a plant's ozone layer, exposing life to direct solar UV and increased cosmic rays until the bulk of the supernovae ejecta arrived perhaps $\sim 10^{3}$ years later (Clark, McCrea & Stephenson 1977). Clark et al. note that supernovae preferentially occur in more dense regions of the galaxy, and in particular they describe a "supernovae zone" trailing behind the compression lane of the galactic spiral arms. Therefore the regions of the galactic bulge and the density fluctuations of the arms pose a higher radiation risk to life than the less dense outer regions. At 8.5 kpc from the Galaxy's center, our Sun is situated in a corotation zone in which it keeps pace with the arms, so does not move in or out of the supernovae zone (Balázs 1986, 1988).

Coupling the accumulation of metals in the Milky Way Galaxy with sterilizing supernovae explosions and taking a 4 ± 1 Gyr timescale for the evolution of complex life, Lineweaver, Fenner & Gibson (2004) find an annular GHZ between 7 and 9 kpc from the center of the galaxy. Within 7 kpc, supernovae extinguish life before complex forms evolve and beyond 9 kpc the low metallicity limits terrestrial planet formation. Lineweaver et al. also argue that high metallicities will limit the habitability of a star because such high metallicities promote the formation of gas giants that spiral inward and destroy any habitable rocky planets. Because only a few non-Jovian mass planets have so far been discovered (Fischer et al. 2003), it is too early to evaluate empirically the last claim. Lineweaver, Fenner & Gibson (2004) find that perhaps 10% of the stars that have formed in the Galaxy are in the GHZ.

6. PLANETS AND PLANETARY HABITATS

Life as we know it appears to be a planetary phenomenon, understood potentially to include planetary satellites, minor planets, and comets. There is an annular zone in our solar system, somewhat misleadingly called the habitable zone (HZ), that

seems particularly welcoming to life because it spans those heliocentric distances where an Earth-size world would be able to maintain surface liquid water (Kasting & Catling 2003). In the usual view, a stabilizing feedback driven by plate tectonics on Earth has allowed CO_2 and H_2O on Earth to maintain greenhouse heating in just the range to permit surface oceans to exist through geological time. (Carbon dioxide levels in the atmosphere are maintained within the range yielding surface temperatures that allow liquid water via a negative feedback involving CO_2 removal by rainfall, precipitation as carbonates, and resupply to the atmosphere due to volcanism subsequent to carbonate subduction.) Venus, too close to the Sun, lost its H_2O owing to a moist or even runaway greenhouse, whereas Mars, too small to maintain substantial geological activity over the age of the solar system, saw its CO_2 atmosphere collapse and is now a freeze-dried desert. It is possible that Mars may have stabilized near the triple point of water because of a different CO_2 feedback mechanism (Kahn 1985).

It now seems clear that there is a "deep, hot biosphere" (Gold 1992) in Earth's subsurface, some components of which may be entirely independent of surface conditions (Chapelle et al. 2002), including solar energy. The biomass (the mass, exclusive of liquid water, present in living things) in Earth's subsurface microbial biosphere is comparable to the entire surface biomass (Whitman, Coleman & Wiebe 1998). These discoveries about life on Earth inform our thinking about the prospects for life elsewhere, making subsurface environments on Mars or subsurface-ocean-bearing moons like Europa seem more plausible (Sagan 1996, Chyba 1997). Even planets that have been ejected from their parent star and are now traveling through interstellar space could still be habitable for subsurface microscopic life provided sufficient geothermal heating to permit liquid water at depth (Stevenson 1999). Planetary life might frequently untether itself from the stars.

6.1. Planets

As of February 2005, good evidence existed for more than 136 extrasolar planets with roughly two more discovered each month (Exoplanets 2005). Because of the selection bias of the Doppler radial velocity technique that is used to discover all but a few of these, nearly all have minimum masses (the measurement determines the planet's mass times the sine of its unknown obital inclination relative to us) consistent with being gas giants—in the range 0.1 to 13 times the mass of Jupiter. Jovian mass planets close to their parent star can induce stellar velocity amplitudes $>30 \text{ m s}^{-1}$, well within observationally obtainable precision. Detection of Saturn-mass planets requires a precision of at least 3 m s^{-1}, and a number of Neptune-mass planets have now also been discovered (Butler et al. 2004, Santos et al. 2004).

Two planetary systems are now known around M stars (Butler et al. 2004, Marcy et al. 2001). The long stellar lifetimes, stability, and abundance of such stars make them especially intriguing from the standpoint of astrobiology. There have been suggestions that planets around such red dwarfs—the most abundant stars in the

Galaxy—might be unsuitable for life, because the habitable zone lies so close to the parent star that any planet within it would be spin locked, so its atmosphere would catastrophically condense out (collapse) on its dark side unless its atmosphere were "exceedingly rich" in CO_2 (Ward & Brownlee 2000). But Joshi, Haberle & Reynolds (1997) used 3D climate models to investigate atmospheric collapse on such worlds, and found that collapse is prevented provided CO_2 pressures are in excess of 30 mbar. For comparison, the venusian, terrestrial, and martian atmospheres currently contain about 92 bar, 0.3 mbar, and 6 mbar CO_2, respectively (Lodders & Fegley 1998).

Especially intriguing is the pulsar timing evidence for a planet in the M4 globular cluster (Sigurdsson et al. 2003). The age of the cluster implies that this planet would have formed some ∼700 Mya after the big bang; this contradicts our metallicity-based expectations (Fischer, Valenti & Marcy 2004) described in Section 5.

Barring catastrophic failure, NASA's upcoming Kepler mission should tell us the frequency of Earth-size worlds around other stars, as well as the semimajor axes of these planets' orbits (NASA ARC 2004). Kepler will search for and monitor transients around 10^5 stars for four years with a launch later this decade. The COROT (COnvection, ROtation & planetary Transits) mission of France's Centre National d'Etudes Spatiales (CNES) should do the same, also this decade but with more limited statistics (CNES 2005). The question of whether other planets like Earth exist has been asked literally for millennia, at least since Aristotle (*De Caelo* 276^{a30}–276^{b24}), though he had principled reasons to rule out the possibility. It is extraordinary that within a few years humanity will no longer have to grope at this question, but instead will know the statistics of other Earths (if any) orbiting within the habitable zones of other stars.

Following the Kepler and COROT missions will be the NASA Terrestrial Planet Finder (TPF; JPL 2005) and the ESA Darwin mission (ESA 2005b). The primary goal of these missions is the direct detection and characterization of Earth-like planets around nearby stars. The TPF mission consists of two complementary observatories: TPF-C is scheduled to launch around 2014 and TPF-I is to be launched around 2020. TPF-C will be a visible-light telescope (8 m by 3.5 m elliptical primary) with a coronograph, allowing direct spectroscopic detection of low-mass planets by blocking the light of the parent star. TPF-I will be a mid-infrared observatory with four formation-flying 3.5 m mirrors that will use nulling intereferometry (as will Darwin) for investigating the atmospheric chemistry and possible chemical biosignatures on detected planets. Estimates of the capability of the mission indicate that Earth-like planets could be detected up to 45 lyr away.

6.2. Habitability

Discussions of planetary habitability have focused on prospects for liquid water. However, for life as we know it, liquid water is but the first of three crucial factors that also include a suite of biogenic elements (such as C, H, N, O, P, and S) and a form of useable free energy. Energy for known life requires that disequilibria

exist within the environment. In taking advantage of these, life hastens the progression of the environment toward thermodynamic equilibrium. (Of course, in some cases—such as the simultaneous production of CH_4 by methanogens and O_2 by photosynthesis—life overall can generate disequilibria as well.) One metric by which the energetics of habitability can be assessed is that of Gibbs Free Energy $G = H - TS$. Here H is enthalpy, S entropy, and T absolute temperature. At constant T and pressure, $\Delta G < 0$ for the system of interest corresponds to $\Delta S > 0$ for the system plus its surroundings. $\Delta G < 0$ for a system tells us that the second law of thermodynamics permits a particular reaction, i.e., that the net entropy of the universe increases. Locally, life constructs microenvironments (e.g., cells) that permit otherwise kinetically inhibited, but nevertheless $\Delta G < 0$, chemical reactions to proceed.

Life has evolved to weave together complex sequences of reactions, some with $\Delta G > 0$, but whose sum results in an overall decrease in G. By fixing carbon and other elements into complex molecules, life does create local decreases in entropy that represent stored energy, or a state of disequilibrium. Ultimately, however, life produces heat and other wastes that more than compensate for the localized decrease in entropy. Globally, the Earth radiates entropy to space, and a crude accounting can be given that shows that the development of life on Earth led to a greater entropy radiation (Ulanowicz & Hannon 1987).

Given that life requires some form of available energy, the search for habitable environments therefore includes the search for abiological processes that can maintain chemical disequilibrium. Terrestrial geology provides an interesting example. Were it not for subduction and volcanism (much—but not all—of which is driven by plate tectonics) the hot, metal-rich, reducing environment of the mantle would not regularly contact the oxidized sediments of the surface, and opportunities for the creation of environments in chemical disequilibrium would be reduced. As a result, biologically useful chemical gradients would also be reduced and life might be less prolific on such a world.

6.3. Mars

Contrast this with Mars, where clearly massive volcanism and possibly plate tectonics were once active even though the planet is now nearly geologically dead (Acuna et al. 1999). The end of plate tectonics and volcanism may have greatly undercut the habitability of Mars by, inter alia, shutting down the negative climate feedback of the CO_2 cycle (Kasting & Catling 2003) and probably greatly reducing the surface availability of biologically useful sources of chemical disequilibria to a low level (Weiss, Yung & Nealson 2000).

Many geologically young features observed on the martian surface may have been caused by changes in solar insolation over time. Milankovitch (named for the twentieth-century Serbian astrophysicist Milutin Milankovitch) cycles—climatic cycles driven by variations in eccentricity, changes in obliquity, and precession—are important for both Earth and Mars (Touma & Wisdom 1993; Laskar, Levrard

& Mustard 2002; Head et al. 2003). Whereas on Earth Milankovitch-driven obliquity and eccentricity variations run through only $\sim$2.5$°$ and from 0.01 to 0.05, respectively, Mars is thought to have experienced over the past 10 Myr variations in obliquity from 13$°$ to 47$°$ and in eccentricity from 0.00 to 0.13 (Howard 2002). Changes in the albedo of layered deposits in the north polar ice cap, revealed by the orbiting Mars Global Surveyor, have been statistically matched to variations in polar temperature resulting from obliquity and eccentricity changes over time (Laskar, Levrard & Mustard 2002). Head et al. (2003) have shown how deposits observed in the northern and southern hemispheres can be explained by an ice age that occurred from approximately 2.1–0.4 Mya. The resulting change in the global stability of water ice would have caused glaciation reaching down to 30$°$–35$°$ latitude. Such glaciation, and resulting subglacial runoff, could have caused observed morphological features attributed to recent liquid water activity (Head et al. 2003, Malin & Edgett 2000).

The landing of the two Mars Exploration Rovers has greatly expanded our understanding of the liquid water history of Mars (MER 2004, Squyres et al. 2004b). In particular, the discovery of sulfate salt deposits (in particular, the mineral jarosite) and geological cross-bedding patterns[4] at the Opportunity Rover landing site of Meridiani Planum has led the science team to conclude that the region was once exposed to a considerable volume of liquid water (MER 2004, Squyres et al. 2004b). The Spirit Rover in Gusev Crater has also detected sulfur-rich compounds and layered deposits that could be indicative of liquid water activity (Squyres et al. 2004a). In the near future (2009–2015), rovers with ranges of km per day should be deployed and a sample return mission may be undertaken.

Ground-based spectroscopy appears to have detected methane in the martian atmosphere via its 3.3 μm band (Mumma et al. 2003) at a 10 ± 3 ppb mixing ratio (Krasnopolsky, Maillard & Owen 2004). Detection at a 10 ± 5 ppb mixing ratio, with local variations ranging from 0 ppb to 30 ppb, has also been achieved with the Mars Express spacecraft (Formisano et al. 2004). Because the CH_4 photochemical lifetime in the martian atmosphere is only 340 years or less, and the CH_4 is inhomogeneously distributed, there must be an active source. Krasnopolsky, Maillard & Owen (2004) view methanogenesis by oases of living subterranean organisms as a plausible explanation, though the less extraordinary hypothesis of abiogenic volcanic or hydrothermal sources cannot now be ruled out. Assuming biomass yields comparable to those of terrestrial organisms, and taking the martian biotic layer to be $\sim$100 m deep and evenly distributed over the planet, they find average cell densities of $\sim 10^{-1}$–10^{-2} cm^{-3}, $\sim 10^5$ times below the sensitivity of the Viking spacecraft GCMS and $\sim 10^{10}$ times lower than densities in rich terrestrial soils. This could imply, were biology the correct interpretation, that the martian surface is largely sterile except for certain as-yet-unidentified oases.

[4]Cross-bedding is a term often used to refer to sedimentary patterns in the rock record which, on Earth, are typically associated with aqueous sedimentary environments.

6.4. Europa

Europa is the most astrobiologically interesting site in our solar system besides Mars, because it likely harbors a contemporary ocean of liquid water of mass about twice that of Earth's oceans beneath an ice shell ∼10–30 km thick. Ganymede and Callisto likely harbor subsurface oceans as well, but these are both deeper and may lack the rock/water interface of Europa's ocean (Chyba & Phillips 2005).

Europa is an ice-covered Moon of Jupiter with a radius of 1560 km, about the size of Earth's Moon. Gravity measurements with the Galileo spacecraft show that Europa is an internally differentiated rocky body with a surface layer of material of density 1000 kg m^{-3} between 80 and 170 km thick (Anderson et al. 1998). The only cosmochemically plausible material with this density is water, consistent with spectroscopy of Europa's surface. Europa is locked in a tidal resonance with the satellites Io and Ganymede, and spin-locked to Jupiter. The resonance forces an orbital eccentricity that leads to tidal flexing and enough internal energy dissipation to maintain most of this ice layer as liquid water (Cassen, Reynolds & Peale 1979, 1980; Ojakangas & Stevenson 1989; Chyba & Phillips 2005). An interior liquid water ocean is consistent with models of features on Europa's geologically young surface (Pappalardo et al. 1999) and, most compellingly, magnetometric measurements of time-varying electrical currents in Europa's interior induced by Jupiter's rotating magnetic field (Kivelson et al. 2000).

Europa's ocean is salty, but it is difficult on the basis of current data to specify its salt concentration. Even if Europa somehow formed devoid of biogenic elements, cometary collisions over the history of the solar system should have delivered sufficient quantities of these elements, despite Europa's low surface gravity, to provide the raw materials for a biosphere (Pierazzo & Chyba 2001). Gaidos, Nealson & Kirschvink (1999) have emphasized the difficulty of identifying sources of chemical disequilibrium on an ice-covered world whose ocean lacks access to the Sun and therefore photosynthesis, and the corresponding difficulty of maintaining a large biomass on Europa. However, sources of chemical disequilibrium driven by charged-particle radiation (Chyba & Phillips 2001, Chyba & Hand 2001) or possible hydrothermal vents (McCollom 1999) can be identified, though the biomass these sources could maintain would be at least several orders of magnitude below that of the Earth. The physics, chemistry, possible biology and future exploration of Europa have been reviewed by Chyba & Phillips (2005).

6.5. Titan

Saturn's largest moon, Titan, is perhaps the most intriguing natural laboratory in our solar system. Due to the cold temperatures (∼94 K) and lack of liquid water, it is not generally believed to be an environment conducive for life. However, Titan does appear to have a complex carbon cycle involving methane clouds, photolytically produced hydrocarbons, and precipitation capable of eroding the hard, mostly water-ice surface. Its 1.5-bar atmosphere is dominated by nitrogen (1.4 bar) with CH_4 the second most abundant constituent. Solar ultraviolet photolysis

irreversibly destroys CH_4, producing an organic haze layer that may then precipitate hydrocarbons to the surface. By one estimate, if such precipitation has occurred over most of Titan's history, then a layer of organic liquids and solids $\sim$800 m thick should cover the surface (Griffith et al. 2003). The persistence of CH_4 in the atmosphere despite UV photolysis requires a source, but at present no liquid reservoirs (lakes or oceans) have been identified by the Cassini spacecraft (Porco et al. 2005). Nevertheless, the paucity of craters combined with linear features characteristic of tectonics, and perhaps river networks, suggests a geologically young ($\sim 10^8$ yr) and active surface. Initial results from the Huygens probe descent imager reveal dramatic dendritic networks and support a possible methane-based meteorological cycle that may have eroded them (Kerr 2005, ESA 2005a). Upon landing, the probe returned images of what appear to be water-ice rocks and data from the surface penetration instrument may indicate a thin crust covering a material similar to wet clay (inspiring a colorful "crème brûlée" analogy.) Analyses from the gas chromatograph/mass spectrometer confirm that CH_4 is, indeed, one of the major compounds in this material. As for the failure to detect large liquid reservoirs from orbit, it may be that seasonal variations in temperature and cloud cover could result in periods of heavy precipitation and weathering. The south polar region of Titan is currently experiencing heavy cloud activity and, as Saturn continues along its orbit, the Cassini spacecraft will monitor changes during Titan-flybys it will make roughly monthly for the next three or more years. Over the Cassini mission lifetime (assuming an extended mission), Saturn will complete approximately one quarter of an orbit, allowing observations of Titan as the southern hemisphere summer comes to a close and temperatures warm toward the equatorial regions, perhaps revealing more clues about processes that shape the surface.

6.6. Planetary Protection

The United States and other space-faring nations are bound by the 1967 Outer Space Treaty (Rauf et al. 2000) to "pursue studies of outer space including the moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth. . . ." In the United States, NASA implements this policy with advice from the Space Sciences Board of the National Research Council.

There is little question that viable microorganisms in spacecraft interiors will survive the cruise from Earth to either Mars (cruise time <1 year) or Europa (cruise time $\sim$3 years). Spores of *Bacillus subtilis* protected against solar radiation survived one year at the $\sim$25% level and six years at the $\sim$1% level on the European Retrievable Carrier (EURECA) and NASA's Long Duration Exposure Facility (LDEF) space missions, respectively (Horneck, Bücker & Reitz 1994; Horneck et al. 1995; for a review of these and other relevant data see Mileikowsky et al. 2000). Precautions must therefore be taken to prevent the confounding of spacecraft life-detection experiments by viable (or dead) microorganisms carried from Earth,

as well as to prevent the risk of introducing microorganisms that could successfully invade possible martian or europan ecosystems (National Research Council 1992, 2000, 2005; Chyba 2003). Precautions must also be taken to prevent the possible back-contamination of Earth with microorganisms carried from Mars in a sample-return mission (National Research Council 1997).

6.7. Rare Earth?

Discussion of the prospects of life or intelligent life in the universe have been strongly influenced in recent years by the anthropic emphasis on the special nature of the Earth, and how observation selection effects prevent us from naively extrapolating the terrestrial environment or evolutionary history to other worlds. We will discuss the biological evolutionary aspects of these discussions below, but here present some cautions concerning the application of these arguments to planetary analysis. In particular, the drive to identify ways in which Earth is special carries dangers when analysts, with good post hoc knowledge, pick the exact element of a complicated system that, if somehow removed, would have especially negative consequences for life. But interpreting this result as evidence of the contingent or fragile nature of biology is misleading if we do not also ask in what other ways the total system would have to have been different for that single element to be missing now, and also what parallel paths there might have been to outcomes similar to the original one. Two examples illustrate the methodological perils of "rare-Earth" reasoning.

Wetherill (1994) showed that solar systems otherwise like our own, but lacking a Jupiter-size world, could subject their interior Earths to a cometary impact flux $\sim 10^3$ times larger than that which would otherwise be the case. This observation has been used (Ward & Brownlee 2000, Gonzalez & Richards 2004) as evidence for how contingent Earth's habitability is. An impact flux $\sim 10^3$ times higher would have severe consequences for complex life, and this may mean that complex life is rare in the universe, as Jupiters may often be lacking.

There are two problems with this argument. One is that comets currently account for only a fraction, and probably a minor fraction, of the impact flux experienced by Earth; the flux is dominated by asteroid collisions (Morrison 2005). Some Earth-crossing objects are thought to be burned-out short-period comets, but most are likely asteroids originating in the asteroid belt. But the asteroid belt likely exists because Jupiter's gravitational stirring prevented the accretion of those objects into a single world. Had Jupiter not been present, the asteroid impact flux experienced by Earth would be lower than today, partly offsetting the putative increased comet flux—though not most of it.

A second problem is that one must ask what the implications for the comet population of the outer solar system would be if Jupiter had never formed. In fact, Wetherill (1994) considers this question and suggests three ways in which this might occur. Two involve jovian core formation too late to capture much nebular gas. The first scenario he considers, however, is one in which Jupiter does not form

because the surface density of the circumstellar gas-dust disk at >5 AU falls off so quickly that the mass of cometesimals in the Jovian region and beyond is too low for objects bigger than "terrestrial planets" to form. In this case, there are simply too few comets in proto-Jupiter's feeding zone to wind up with a Jupiter. The question then becomes how many of the candidate early Solar Systems that lead to this outcome still produce enough comets for a much higher collision flux on Earth? How many of those candidates fail to form a Jupiter because the disk out of which the comets and planets accrete gets truncated or falls off in mass so quickly beyond a certain heliocentric distance that the inner planets do not experience much impact flux after a very early heavy bombardment? And how frequent or rare are these various possibilities? Without answering these questions, theoretically or empirically, we cannot assess whether an Earth with a low-enough impact flux for advanced life to arise is rare or not.

Wetherill (1994) also considers other scenarios, including one in which Jupiter and Saturn form, but in which the nebula mass distribution is such that Uranus and Neptune grow to be the size of Saturn. In that scenario, because of the Saturnian-size Neptune and Uranus, the Earth experiences essentially no comet flux subsequent to a very early bombardment. There are a variety of possible solar systems, some with more, and some with less, cometary flux. We do not yet know enough to know what is "rare" or common, or whether some common scenarios might be more favorable to life than our own system's configuration.

A second example of "rare-Earth" reasoning concerns conclusions drawn from the important discovery of the obliquity-stabilizing effect of Earth's Moon (Laskar & Robutel 1993; Laskar, Joutel & Robutel 1993). The inference is made (Ward & Brownlee 2000, Gonzalez & Richards 2004) that complex life must therefore be rare, on the grounds of the assertion that Earths with Moon-size satellites must be rare, and that in the Moon's absence wild obliquity fluctuations would occur that would render the environment too inconstant for the evolution of complex or intelligent life. [There is now observational evidence that large planetesimal collisions in other solar systems are common at the end of planetary accretion (Rieke et al. 2005), but, of course, there are currently no statistical data about the frequency or nature of planet–moon combinations that may result.]

But again one must ask what Earth may have been like had the Moon never formed—not what the Earth would look like if today one somehow plucked away the Moon. Laskar & Robutel (1993) show that Moonless Earths rotating with periods <12 hr may be stable against chaotic obliquity fluctuations for a large range of obliquity angles. Of course the current Earth's period is 24 hr, so if we pluck away the Moon today chaos sets in. But if the Moon had never formed, what would Earth's rotational velocity have been? A simple angular momentum conservation calculation shows that if one tidally evolves the lunar orbit back in time from its current position at 60 $R_\oplus$ to an early orbit at 10 $R_\oplus$, Earth's day would have been about 7 hr long, giving an Earth likely stable against chaotic obliquity fluctuations. Touma's (2000) simulations of the Earth–Moon system take Earth's initial rotation period to be 5.0 hr, with the Moon at 3.5 $R_\oplus$. Of course, this does

not demonstrate that Earth's rotational period would have been this short had the Moon never formed; it is difficult to estimate Earth's primordial rotation in the absence of the putative Moon-forming impact [see Lissauer, Dones & Ohtsuki (2000) for a discussion of the issues]. But it shows the arbitrary nature of reaching conclusions about Earth's rarity by plucking away the Moon today, rather than, say, shortly after lunar formation.

7. THE ORIGIN OF LIFE

Throughout our discussion of planetary habitability, we have so far failed to emphasize that determining an environment to be habitable for modern microorganisms does not mean that the origin of life could have occurred in that environment. The problems of habitability and origins are distinct.

The origin of life remains one of the most fundamental questions in astrobiology, and indeed in all of science. Here we address certain recent developments but refer the reader to more thorough reviews (Chyba & McDonald 1995; Deamer 1997; Wills & Bada 2000; Segre, Deamer & Lancet 2001). Both a top-down approach (deconstructing life) and a bottom-up approach (building life) have been pursued. We begin by reviewing progress in the bottom-up approach.

7.1. Bottoms Up

The 'primordial soup' theory has dominated scientific opinion since Oparin (1924) and Haldane (1929), and especially since the experimental work of Miller and Urey (Miller 1953, Miller & Urey 1959). Even Darwin speculated about a "warm pond" as the beginning of it all (Darwin 1871). The vast bulk of the primordial soup work to date (Wills & Bada 2000) has at its root the same general hypothesis: if we take prebiotically plausible simple molecules (e.g., hydrogen-rich compounds such as CH_4 and ammonia, NH_3) and apply energy (e.g., spark discharge, UV irradiation, or an impact shock), larger building blocks leading toward life will be synthesized (e.g., amino acids or nucleic acid bases). Optimistic extrapolations envisioned that further reactions would lead to more complex compounds (e.g., proteins[5] and nucleic acids[6]) and eventually life itself would emerge. Some important experimental progress along these lines was demonstrated (e.g., Oró 1961), but
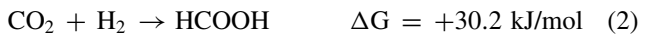
---

[5]Proteins consist of one or more polypeptides; a polypeptide is a chain of amino acids linked together by a particular kind of covalent bond (called a peptide bond) between the carboxyl and amino groups on the successive amino acids. Proteins are responsible for most of the metabolism in modern cells.

[6]Nucleic acids are polymers of nucleotides, each of which consists of a sugar (e.g., ribose or deoxyribose), a phospate, and a nitrogenous base. Ribonucleic acid (RNA) and deoxyribonucleic acid (DNA) are both present in modern cells, with DNA being the repository of genetic information and RNA mediating the transfer of genetic information from DNA to the formation of proteins.

synthesizing proteins and nucleic acids under realistic prebiotic conditions remains challenging (Chyba & McDonald 1995). Moreover, as conditions on early Earth were further studied, the early atmosphere came to be viewed as rich in CO_2 rather than in the hydrogen-rich (reducing) compounds that Miller and Urey used in their initial experiments (Kasting & Catling 2003). The production of organic molecules in these less-reducing atmospheres is orders of magnitude less efficient than in the reducing case (Stribling & Miller 1987). This in turn led to more attention being placed on the inventory of organics provided Earth from exogenous sources such as comets (Chyba et al. 1990; Thomas, Chyba & McKay 1997) and interplanetary dust particles (Chyba & Sagan 1992), suggesting a possible connection between the terrestrial origin of life and interstellar chemistry (Ehrenfreund et al. 2002). In some plausible early atmosphere models, the terrestrial inventory of at least some prebiotic molecules, such as certain amino acids, may have been dominated by cometary input (Pierazzo & Chyba 1999). However, the hydrogen content of the early atmosphere remains uncertain (Tian et al. 2005), so it is wisest to consider a range of atmospheric models and their differing consequences (Chyba & Sagan 1992).

Among the issues that face the soup theory—and for that matter, any theory of life's origin—are questions of the evolution of genetic control and cellular organization. Genes[7] provide the information needed for production and replication, whereas components of cellular organization (be they lipids or proteins) provide the protection needed for survival. Over the past two decades several workers have approached these problems by prioritizing the role of energy flow, and hence metabolism, as the key primordial process for understanding the origins of life. Theories that emphasize the origin of metabolism represent a very different approach to the problem of origins than do the building-blocks-first theories.

Wächtershäuser (1988, 1990) proposed a scheme based on the reaction of aqueous CO_2 with FeS and H_2S. Reactions leading to the formation of prebiotically interesting compounds such as formic acid are energetically favorable, as indicated by a negative change in Gibbs free energy. As one simplified example, consider the three reactions:

$$FeS + H_2S \rightarrow FeS_2 + H_2 \qquad \Delta G = -41.9 \text{ kJ/mol} \quad (1)$$

$$CO_2 + H_2 \rightarrow HCOOH \qquad \Delta G = +30.2 \text{ kJ/mol} \quad (2)$$

$$CO_2 + FeS + H_2S \rightarrow FeS_2 + HCOOH \qquad \Delta G = -11.7 \text{ kJ/mol} \quad (3)$$

The first of these reactions is entropically favorable ($\Delta G < 0$ for the system at constant pressure and temperature, so $\Delta S > 0$ for the system plus surroundings), but produces no organics. The second fixes carbon to produce the simple organic formic acid, but is not entropically favorable. The third couples the first two

---

[7]A gene is a unit of heredity; in the modern cell it is a segment of DNA that specifies (via the genetic code) the sequence of amino acids in a particular protein or polypeptide chain, or the sequence of nucleotides in a particular RNA molecule.

reactions to provide an entropically favored way to produce organic molecules. The resulting pyrite (FeS_2) and simple organic compounds (here, formic acid) could then be bound electrostatically by the attraction of the positively charged pyrite surface to the negatively charged organic compounds. Concentration of products on a 2-dimensional surface results in a putative surface chemistry that could prevent dilution of products in the ocean. This model of mineral surface catalysis is also attractive in principle because as the reactions increase in complexity, lipid-like compounds could form and eventually a membrane or proto-cellular structure could be synthesized. However, much experimental work remains to be done to test the claims of this scheme (de Duve & Miller 1991, Chyba & McDonald 1995). Huber & Wächtershäuser (1997, 1998) have so far shown that they can produce acetic acid and form amino acid chains (peptides) under certain conditions.

Wächtershäuser's proposals are intriguing in that a clear line is postulated between the inorganic mineral world and the production of an organic, and eventually living, world. Weber (2000) also begins with metabolism as a motivating premise for the emergence of life, but he argues for sugars as the optimal, most energetically useful substrate from which to synthesize more complex compounds. In particular, he has demonstrated that under ambient, room temperature and pressure conditions he can create a "one-pot" reaction capable of synthesizing sugars from formaldehyde and glycolaldehyde, and then amino acids from the resulting sugars. Though peptides have not yet been synthesized, earlier results utilizing sulfur (thiols) give reason for optimism (Weber 1998).

We conclude our survey of the bottom-up approach to the origin of life by considering compartmentalization. Contemporary life on Earth distinguishes itself from the environment, and regulates its communication with the environment, through compartmentalization. Such vesicles, or cells, are important for maintaining useful energy gradients and for concentrating biologically useful compounds. The lipids from which vesicle membranes are formed would have been prebiotically available on early Earth (Hargreaves, Mulvihill & Deamer 1977; Deamer & Oró 1980) and encapsulation of peptides and nucleic acids was likely a critical step toward living systems (Segre, Deamer & Lancet 2001). Simulating prebiotic conditions, Deamer (1997) has shown how endogenous or exogenous amphiphilic (soap-like) compounds will self-organize into membrane structures capable of housing genetic material. Furthermore, vesicle formation has been shown to occur using organics found in carbonaceous chondrite meteorites (Deamer & Pashley 1989). This work has also been extended to simulated interstellar conditions, demonstrating that primitive membrane structures can form from amphiphilic molecules in UV-irradiated interstellar/precometary ices (Dworkin et al. 2001). The issue of compartmentalization for early life thus already seems to have plausible resolutions (via endogenous and/or exogenous sources), and this is an important advance. The tremendous task remains to see how proto-cellular structures coupled with genetic material can then lead to self-replicating systems.

7.2. Top Down

The top-down approach to the origin of life has two foci: (*a*) deconstructing life as we know it into the smallest possible units that still exhibit some characteristics of living systems; and (*b*) mapping the genetic relationship of all life on Earth in an attempt to elucidate the properties of the last common ancestor.

The discovery that RNA molecules can show catalytic activity and the elucidation of that discovery have been among the greatest successes of the deconstructionist approach. Ribozyme, or RNA enzyme,[8] molecules are capable of catalytic activity as well as information storage, implying a solution to the chicken-or-egg puzzle that had long haunted work in origins (Dyson 1985)—proteins first or DNA first? In the labs of both Thomas Cech and Sidney Altman during the 1980s, it was discovered that some sequences of RNA had the ability both to self-splice and to catalyze protein synthesis (Altman et al. 1989, Cech 1993). An "RNA world" where RNA molecules performed the functions of both present-day proteins (e.g., acting as enzymes to catalyze reactions) and DNA (acting to store genetic information) now seems a likely evolutionary predecessor to our more specialized DNA-protein world (Gilbert 1986). Nevertheless, the prebiotic origin of the RNA that populated the putative RNA world remains mysterious. Perhaps primordial RNA evolved in a "naked" environment and then later managed to create a self-containing envelope that was advantageous for selection in new environments (James & Ellington 1995); but it seems likely that RNA was in fact preceded by some other replicating system, as RNA is so difficult to make under realistic prebiotic conditions (Shaprio 1988, Chyba & McDonald 1995).

At the level of the complete cell, efforts are now underway to strip down a microbial genome to reveal the minimal set of genes necessary for complete cellular functionality (Hutchison et al. 1999, Marshall 2002). If successful, this project could create the first functioning artificial genome, possibly bringing us closer to understanding how the genetic code coordinates the process we associate with living systems.

7.3. The Tree of Life

The function of certain molecules (such as those in the ribosome[9]) is so critical in modern organisms that regions within the corresponding gene evolve only very slowly through time. Such regions among different organisms can be intercompared, DNA base by base, and the number of differences between two DNA sequences can be used to gauge the "evolutionary distance" between organisms

---

[8]An enzyme is a catalyst that promotes specific reactions or groups of reactions. Modern enzymes are usually proteins, but it is now clear that some RNA molecules can serve as enzymes as well.

[9]The ribosome is a complex assemblage of RNA and protein that is the site of protein synthesis in the cell.

(Pace 1997). The resulting phylogenetic[10] map for a key part of the ribosome has come to be known as the "tree of life." There is no explicit temporal information in this tree. As emphasized by Woese (1998), the primary branches of the universal tree of life reflect "the common history of central components of the ribosome, components of the transcription apparatus, and a few other genes. But that is all."

The current genetic region of choice for creating the putatively universal phylogenetic tree for all life on Earth is that part of the DNA that codes for the 16S small subunit ribosomal RNA (rRNA). This region of the DNA would be highly conserved, because the ribosome is the crucial molecule for the synthesis of proteins in the cell. Even better, the 16S rRNA sequence is abundant, it is coded for in all known cell types, and it contains smaller genetic regions that evolve at a range of rates (Woese 1987, Doolittle 1999). The resulting tree shows three large branches, or "domains": Bacteria, Archaea, and Eukarya. Archaea had been misinterpreted as bacteria until DNA comparisons showed otherwise.

The point at which major branches converge represents the last common ancestor for those two branches; thus the organisms located closest to the most basal branches of the tree might be representative of the most ancient life forms on Earth. These microbes, with names such as *Aquifex* and *Thermatoga*, have been discovered in hot spring environments such as those in Yellowstone or at the deep-sea hydrothermal vents along the mid-ocean ridges. It is unclear whether this means that life originated in such environments (Nisbet & Sleep 2001). The phylogenetic evidence at most suggests that the last common ancestor lived in such an environment, and it could be that the heavy bombardment to which early Earth was subject created an "impact bottleneck" through which only those organisms living in the deep (and therefore hot) subsurface could have survived (Sagan 1974, Maher & Stevenson 1988, Sleep et al. 1989).

Though significant progress has been made in deriving the 16S rRNA tree (Pace 1997), large uncertainties remain, in part because of evidence for widespread horizontal gene transfer (HGT) (Gogarten, Doolittle & Lawrence 2002). HGT—also referred to as lateral gene transfer in the case of intraspecies events—involves the transfer of nucleotide strands with lengths of 10^2–10^4 base pairs from one organism to another (Lawrence & Ochman 1998). With the process of HGT acting on and between populations, the view of descent from a common ancestor is challenged. Genetic material is not just being passed vertically through time during cell replication, it is also being transferred laterally at various points in time. Indeed, it has been declared that this process is responsible for creating "mayhem at the root" of our tree of life (Doolittle 1999), and the "last common ancestor" may have been a promiscuously gene-exchanging community (Woese 1998). The fact that the microbe *Deinococcus radiodurans* has been found to contain plant genes and *Mycobacterium tuberculosis* has been found to contain at least eight human genes confounds attempts to reconstruct evolutionary history based on genomes (Pennisi 1999). Nevertheless, some have argued that a meta approach to genomic analysis may still be able to yield the correct outline of the tree of life. So far, however, it

---

[10]The term phylogeny refers to the evolutionary relationships among a group of organisms.

appears that the full genomic tree parallels the rRNA tree (Pennisi 1999). Gogarten, Doolittle & Lawrence (2002) have argued that rRNA genes themselves may have experienced large-scale gene transfer and thus "perhaps rRNA genes appear to be such useful molecules for prokaryotic taxonomy precisely because they are mosaics and reflect the mosaic character of the genome as a whole." Mapping more genomes will be the key to evaluating the rRNA tree.

Throughout discussions of lessons learned from DNA phylogenies, it is important to remember the limitations of the polymerase chain reaction (PCR) technique used to replicate and amplify the DNA needed for phylogenetic analysis. For the technique to work, the DNA of the unknown target organism—many of which have never been cultured in the laboratory, and may be known only through their 16S DNA sequences—must have at least some small shared sequences in common with known DNA sequences. If an organism does not have these shared sequences it will go undiscovered until our genomic knowledge expands to include "primer" DNA sequences that will find such organisms—assuming, of course, that they have DNA to begin with.

8. TIMESCALE FOR THE ORIGIN OF LIFE

In order for life as we know it to exist, the timescale for the origin of life must be short compared to the lifetime of its parent star. Lazcano & Miller (1994) have argued on the basis of prebiotic chemistry that the origin of life on Earth must have taken less than $\sim$10 Myr, but because we do not understand the steps leading to the RNA world, such estimates cannot be rigorously defended (Orgel 1998). Obviously high-mass stars provide dramatically shorter periods of time during which a planetary environment might permit the origin of life.

In the case of life on Earth, the time window for the origin of life is constrained by planetary formation models on the far end, and the available geological evidence for life on the near end. The origin of life on Earth was likely impossible prior to the solidification of Earth's magma ocean $\sim$10^8 years after terrestrial accretion (Solomatov 2000). Subsequent to that time, the heavy bombardment, and in particular impacts of objects large enough to have evaporated Earth's oceans, could have frustrated the origins of life until $\sim$3.8–3.9 Gya (Sagan 1974, Maher & Stevenson 1988), although such conclusions vary with the statistics of small numbers (Sleep et al. 1989).

On the other side of the window for life's origin, one can search for signatures of ancient life in the rock record, typically those of morphology, molecular fossils, or stable isotope geochemistry. A combination of evidence based on microfossils, stromatolites,[11] and isotopic fractionation have led some to argue that life on Earth may have been well established by 3.8–3.5 Gya (Schopf 1993,

---

[11]Stromatolites are microbial mat communities consisting of photosynthetic bacteria, other microorganisms, and sediments, often domical and usually with a laminar structure. Both fossilized and extant stromatolites exist.

Mojzsis et al. 1996, Rosing 1999). Over the past decade, these lines of evidence have become increasingly controversial (Brasier et al. 2002; van Zuilen, Lepland & Arrhenius 2002), so we emphasize them in this review, working backward in time toward increasingly controversial evidence for the presence of life on Earth.

It is broadly agreed that robust and abundant fossil evidence is present in ~3 Gya rocks, that less certain fossil evidence exists in 3.5 Gya rocks, and that substantially controversial isotopic evidence exists in 3.8 Gya rocks. Carbonate deposits in ~3 Gya South African sedimentary rocks show well-preserved stromatolites that match well with similar, known biogenic structures seen in much younger rocks and even in modern aqueous sedimentary environments (Beukes & Lowe 1989). Structures of similar age and morphology are also seen in the ~3.0 Gya rocks of Steep Rock, Ontario (Wilks & Nisbet 1985). Stromatolites have been found in 3.5 Gya rocks, but modeling work has shown that such complex sedimentary structures could also potentially be produced abiogenically (Grotzinger & Rothman 1996), and it is difficult to be sure whether these are of biological origin (Knoll 2003).

Moving further back in time, the evidence becomes more difficult to assess. Claims for the Earth's oldest fossils have been made for ~3.5 Gya filamentous structures in both the Apex cherts [granular, sedimentary silica (SiO_2)] of the Warrawoona Group of Western Australia (Schopf & Packer 1987, Schopf 1993) and the Onverwacht Group, Barberton Mountain Land, South Africa (Walsh & Lowe 1985). To date, these represent the most ancient credible morphological microfossils, although the question of their biogenicity remains to be entirely resolved. The Apex microfossils are now the focus of some controversy (Brasier et al. 2002). Originally it was claimed that the proposed microfossils represented ancient cyanobacteria within a sedimentary, stromatolitic environment, but it now appears that the Apex chert may be hydrothermal in origin (which may call the cyanobacterial interpretation into question, but does not in itself rule them out as microfossils), opening the possibility that the structures might also be explained by physical processes resulting in chains of crystal formation. Schopf & Packer (1987) and Schopf (1993) argue for a biological origin with photomicrographs of apparently discrete, cellular structures aligned in chains of curving filaments. In bulk, however, these filaments are found to be randomly oriented and irregularly distributed, unlike some Proterozoic (2500 Mya to 543 Mya) and modern cyanobacterial assemblages, although randomly oriented filament in modern microbial mats are not unknown. Brasier et al. (2002) find the filamentous structures in several different geologic clasts as well as the surrounding chert matrix, challenging the argument (Schopf 1993) that the structures represent fossils preserved in an older unit that was then transported and redeposited in a bedded chert. Brasier et al. (2002) reinterpret the microfossil-like structures as the byproduct of amorphous graphite mixing with metal-rich hydrothermal vein cherts and volcanic glass, and cite several examples of branched filamentous structures, which they argue rebuts

the morphological claim that these derive from ancient bacteria. Although they do find δ^{13}C values[12] of –30‰ to –26‰, compatible with biogenic fractionation of the carbon, they argue that such fractionation could also occur when volcanic CO_2 interacts with high-temperature (250–350°C) hydrothermal fluids. Responding to critics of a biogenic origin for the structures, Schopf et al. (2002) utilized Laser-Raman imagery of the filaments to argue that they were indeed carbonaceous (kerogenous) structures. Brasier et al. (2002) also utilized high-resolution Raman spectroscopy but found that the carbon signature is not limited to the filaments, consequently questioning the biogenic origin of the carbon.

The morphological case for ancient microfossils may continue to prove controversial for some time. Recent work demonstrating facile, nonbiological synthesis of complex, filamentous silica-carbonate structures blurs the line segregating biogenic morphologies from inorganically produced structures (Garcia-Ruiz et al. 2003). One line of evidence that could prove compelling, however, is that of the discrete cellular compartmentalization of the mineralized carbon. Many of the abiogenic structures of Garcia-Ruiz et al. (2003) are continuous, spiraling filaments that only give the appearance of being lines of discrete cells.

The discovery of key biomarker molecules, such as the terpanoids, hopanes, and steranes[13] derived from cellular and membrane lipids, can provide strong evidence for the past presence of life in ancient sediments. Such biomarkers have been used to argue for the advent of cyanobacteria, and therefore oxgenic photosynthesis, by 2.5 Gya and for the emergence of eukaryotes at 2.7 Gya (Brocks et al. 1999, Summons et al. 1999). However, increasingly ancient rocks generally make such tests increasingly difficult to perform, and the 3.5 Gya Warawoona rocks have in particular been too metamorphosed to permit the survival of such biomarkers (Knoll 2003).

Stable isotope geochemistry is the only technique to which appeal can be made to argue for evidence of life at 3.8–3.9 Gya (Schidlowski 1988, Mojzsis et al. 1996, Rosing 1999), because these ancient rocks have been so heavily metamorphosed that fossil evidence cannot have survived to the present day. Graphite in the 3.8 Gya highly metamorphosed sedimentary rocks (metasediments) of Western Greenland was found to have an isotopic signature of δ^{13}C $\approx$ −28‰, seemingly indicative of biological activity early in Earth's history (Schidlowski 1988). Mojzsis et al. (1996) claimed that graphite particles were found within a banded iron formation and in apatite grains, creating a compelling geological context for the proposed

---

[12]Carbon-13 isotope geochemistry utilizes the difference of ^{13}C isotopes in the sample relative to the ^{13}C in a standard sample from the Cretaceous known as the Peedee Belemnite ($^{13}C_{PDB}$) to provide evidence for biological isotopic fractionation. For example, photosynthesis creates a δ^{13}C fractionation of roughly -25‰ because it kinetically favors the ^{12}C atom. Formally, $\delta^{13}C \equiv 1000[(^{13}C/^{12}C)_{sample}/(^{13}C/^{12}C)_{PDB} - 1]$.

[13]These molecules consist of linked carbon ring structures that are stable over geologic timescales. Terpanes are characteristic of cell membranes used by microbes in the Archaeal domain, hopanes for the domain of Bacteria, and steranes for the Eukaryotes.

biosignature.[14] The formation of the graphite, in this scenario, would have resulted from metamorphosed carbonaceous material originally derived from microbial life.

However, as more data on these rocks have become available, some have argued against the biogenic nature of the graphite (Fedo & Whitehouse 2002; van Zuilen, Lepland & Arrhenius 2002). Primary among these criticisms is that a $\delta^{13}C$ of $-10‰$ to $-12‰$ in graphite can be achieved when the mineral siderite ($FeCO_3$) is thermally decomposed at temperatures above $450°C$ (van Zuilen, Lepland & Arrhenius 2002):

$$6FeCO_3 \rightarrow 2Fe_3O_4 + 5CO_2 + C. \qquad (4)$$
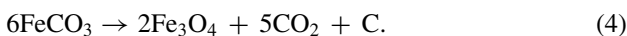
The resulting magnetite (Fe_3O_4) and istopically light graphite (C) remain in the rock while the CO_2 escapes. Van Zuilen et al. also suggest that recent organic material possibly emplaced by percolating groundwater may also play a role in the especially light graphite values. Though the original claims for life reported $\delta^{13}C \approx -28‰$ (Schidlowski 1988, Mojzsis et al. 1996), more recent analysis of the graphite particles with a larger number of samples has found the signature to be considerably more varied, ranging from $\delta^{13}C$ of -18 to $+2‰$ (Ueno et al. 2002). This is in agreement with the abiogenic fractionation process described above. Implicit in this process is that the observed carbonates are not sedimentary, but rather metasomatic in origin (van Zuilen, Lepland & Arrhenius 2002). That is, they are the result of high temperature fluids interacting with iron-rich material, and not the result of iron precipitation and sedimentation as is often associated with early microbial communities. Perhaps the most disturbing proposed evidence against an ancient biosignature in the Akilia rocks is the claim that the apatite crystals do not, in fact, contain graphite inclusions (Lepland et al. 2005). Moorbath (2005) argues that there is only one site left in the Isua region where an argument for an isotopic biosignature older than 3.7 Gyr remains possible (Rosing & Frei 2004).

Why does the timing of the earliest evidence for the origin of life on Earth matter for astrobiology? It is too glib to claim that if the origin of life took place on Earth immediately after the end of the heavy bombardment, then the origin of life must be "easy," so that the prospects for life elsewhere are increased. As discussed previously with respect to the anthropic principle, our strong observer bias calls such claims into question. However, the time window for the origin of life is important when considering plausibility arguments for other putative venues for life in the solar system or beyond. For example, if the evidence for life at 3.8 Gya were compelling, that would mean that the timescale for the origin of life could be as short as $\sim10^8$ years or less, whereas if life did not originate until 3.45 Gya or 3.1 Gya, that timescale might be $\sim10^9$ years. Some large asteroids and perhaps comets in the early solar system probably sustained liquid water interiors

---

[14]Banded iron formations are sedimentary rocks rich in oxidized iron that may therefore be indicative of the onset of oxygenic photosynthesis. Apatite, a form of calcium phosphate, is a mineral often found in association with microbial activity.

for $\sim 10^8$ years before entirely freezing. Whether one expects substantial progress toward the origin of life in such bodies (so far not convincingly seen in meteorite samples), or whether these objects may provide natural tests of certain subsurface origin hypotheses, will depend in part on the timescale demonstrated for the origin of life on Earth (Chyba & McDonald 1995).

9. COUPLED EVOLUTION OF LIFE AND ITS PLANETARY ENVIRONMENT

For the first ~ 3 Gyr after the emergence of life on Earth, biological systems consisted of single-celled microbes, although macroscopic consortia such as mats or stromatolites appear to have been common. Symbioses at the cellular level, such as the endosymbiotic incorporation of cyanobacteria into a functional chloroplast or proteobacteria into mitochondria, were major evolutionary innovations (Margulis 1999). Today, the continuing importance of symbiotic relationships are perhaps most dramatically represented in the ecology of the deep-sea hydrothermal vents (Van Dover 2000).

As the biosphere expanded, life became a key factor in regulating the environment and climate. This is nowhere more apparent than in the oxygenation of the atmosphere by photosynthesizing organisms, though this oxygen source also had to be mated to a geological sequestration of organic carbon (for reviews see Kasting & Catling 2003, Knoll 2003). Life on Earth now plays a key role in many of the chemical cycles of the planet and some have argued that life itself regulates the habitability of our planet (Lovelock 2003). The possibility of life on contemporary Mars suggests that such regulation can be overwhelmed by planetary geological evolution.

10. INTELLIGENCE IN THE UNIVERSE

Unless one takes the view that intelligence is independent of natural selection, the study of the evolution and prevalence of intelligence (and technical intelligence) on Earth and elsewhere is a natural component of astrobiology. This is all the more so as human intelligence is now strongly shaping the terrestrial environment and biosphere. Indeed, Crutzen (2002) defines our current geological period as the "anthropocene," so strong and pervasive are humanity's effects. Palumbi (2001) argues that humans have become Earth's "greatest evolutionary force" dramatically accelerating evolutionary change in other species, and a consortium of ecologists calls for a shift in ecological studies from increasingly rare undisturbed ecosystems to a future environment that "will largely consist of human-influenced ecosystems" (Palmer et al. 2004). Nor will this influence necessarily stop with Earth; advocates of terraforming consider the intentional alteration of the environments of other worlds (McKay, Toon & Kasting 1991). In the previous section we recalled the

coupled evolution of terrestrial life and its planetary environment. Intelligent life is now playing a similar role, but the timescale for its influence is shorter by orders of magnitude than has been true for that of nontechnical biology in the past (Palumbi 2001). Progress toward closing the cycle of humanity's "technological nutrients" is being made, but much remains to be done (McDonough & Braungart 2002).

As is the case with extraterrestrial life of any kind, we currently do not know whether intelligent life is common or extremely rare in the universe. There is now a vast literature that endeavors to address this question. We group many of these attempts into five major categories, discussed in the following subsections.

10.1. The Large Number Argument

It may seem intuitive that in a Galaxy of hundreds of billions of stars, it would be extraordinary for Earth to host the only intelligent species or even the only technical civilization. Nevertheless, because of observer bias, this conclusion does not follow from what we know. How likely is it that that the probability of evolving a technical civilization is greater than $\sim 10^{-11}$ per star? In principle, it would be possible to learn enough about the factors determining the answer to this question to estimate the number of technical civilizations in the Galaxy. This is the promise of the Drake equation, which Frank Drake first wrote down as a meeting agenda for the first small conference addressing this issue in 1961 (Drake & Sobel 1992). The Drake equation is $N = R_* f_p n_e f_l f_i f_c L$, where N is the number of technically communicative civilizations in the galaxy, R_* is the rate of star formation in the galaxy, f_p is the fraction of those stars around which planets form, n_e is the number of planets in such systems suitable for the origin of life, f_l is the fraction of those planets on which life actually originates, f_i is the fraction of those on which life evolves intelligence, f_c is the fraction of those that become communicative across interstellar distances, and L is the average lifetime of a communicative civilization (Sagan 1973). Obviously this equation does not have the status of an equation like that of the ideal gas law, which posits a relationship among the pressure, volume, and temperature of gases in the physical world and so is subject to potential falsification. The Drake equation, rather, is a type of "Fermi problem," an example of the sort of back-of-the-envelope reasoning made famous by Enrico Fermi (Webb 2002). The best-known example of a Fermi problem was the question "how many piano tuners are there in the city of Chicago?" Though the answer may be difficult to guess a priori, by breaking the calculation down into a product of numbers whose order of magnitude may be estimated (such as the population of Chicago, the number of people per family, the fraction of families that own pianos, etc.) one can make a credible estimate.

This goal is not, however, currently realizable with the Drake equation. Though the three factors R_*, f_p, and n_e can be assigned credible estimates on the basis of what is already known, the remaining factors for now can only be guessed. L, in particular, moves us into the realm of extraterrestrial morality, sociology, and political science, which remain underdeveloped fields, despite brave attempts

(Ruse 1985). L could only be known by gaining observational knowledge of other civilizations. At its upper end we might imagine that L could be as long as a G-class star lifetime (and perhaps longer), $\sim 10^{10}$ years. At its lower end it could be as short as the interval between the invention of radio and the mass production of thermonuclear weapons; this interval might be as short as $\sim 10^2$ years or even shorter. The average value of L in the Galaxy might be anywhere in this interval, so that uncertainties in L alone introduce at least an eight-order-of-magnitude uncertainty into estimates of N. However, it is the average value of L that matters; if only a small fraction of intelligent civilizations have a large L, the average could still be very large. The Drake equation sheds light on the key issues for determining N and makes a sobering connection between N and the lifetime of civilizations. In the face of the uncertainties the Drake equation illuminates, the large-numbers argument cannot in itself resolve questions about the frequency of either communicable civilizations or intelligence in the galaxy.

10.2. Anthropic Arguments

Attempts have been made to use anthropic reasoning to reach conclusions about the frequency of intelligent life in the universe. Carter's (1983) argument has received the most attention. Greatly condensed, the idea of his argument is that we expect there to be no correlation between the lifetime $\tau_\odot$ of a main-sequence star like our Sun, and the timescale τ_1 for biological evolution, say to the point of our own technical intelligence. Because these timescales are independent, we expect either $\tau_1 \gg \tau_\odot$, or $\tau_1 \ll \tau_\odot$, but the chances of $\tau_1 \approx \tau_\odot$ would seem vanishingly small. Yet on Earth, $\tau_1 \approx \tau_\odot$ holds to within about a factor of two. If in general $\tau_1 \ll \tau_\odot$, then it would be surprising for the first system observed to have $\tau_1 \approx \tau_\odot$ [and, we might add, $\tau_1 \ll \tau_\odot$ could not hold in any case, for reasons (such as the Earth's early magma ocean; Solomatov 2000) having to do with the utter uninhabitability of the Earth for its first $\sim 10^8$ years]. But then it must be generally true that $\tau_1 \gg \tau_\odot$, which in turn means that human civilization evolved in an exceptionally short period of time compared to the average, an event perhaps so unlikely that other civilizations might well not exist elsewhere in the galaxy.

Various objections to this and related arguments may be found in the literature (Bostrom 2002), but perhaps the one most subject to scientific investigation is Livio's (1999) approach of questioning the independence of τ_1 and $\tau_\odot$. Livio's argument that stellar luminosity is a driver of evolution is interesting but, by his own description, only intended to demonstrate that a relationship between τ_1 and $\tau_\odot$ could exist.

We emphasize the centrality of this issue by an analogy. Prior to the development of the geological theory of plate tectonics (Oreskes 2003), one could have proposed a Carter-like argument to putatively demonstrate that mountains must be unique to the Earth. After all, there was no obvious connection between the rapidity of mountain building and the solar lifetime, and because mountains could not have formed during Earth's magma ocean, the timescale for mountain building could

not be less than $\sim 10^8$ years. Therefore, the argument would have run, because the timescale for mountain building cannot be $\ll \tau_{\odot}$, it must typically be $\gg \tau_{\odot}$. Mountains should therefore be unique to Earth. But now we understand mountain building to be caused by compression from the collision of tectonic plates or by volcanic activity (which in some cases, but only some, is associated with plate subduction). Plate tectonics and volcanism are fueled by the interior heating of the Earth. Most of this heating is due to radioactive decay, but 25–30% is heating leftover from terrestrial accretion (Turcotte & Schubert 1982). But the latter was determined by the specific kinetic energies (velocities) of accreting planetesimals in the terrestrial feeding zone, and the planetesimal velocities in their Keplerian orbits depended on the mass of the Sun—which also determines the Sun's lifetime, as stellar luminosity is a strong function of mass. Thus, the timescales of two seemingly unrelated processes—the timescale for mountain building and the lifetime of the Sun—are in fact correlated by their dependence on the mass of the Sun.

Livio's attempted rebuttal to Carter's argument is not decisive, and our analogy is hardly ironclad, but they are reminders that in our present state of ignorance regarding the nature of life, the origin of life, and the evolution of intelligence, it is premature to express confidence that evolutionary timescales and stellar lifetimes are independent. Indeed, as Livio (1999) cautions, it might be surprising if biological evolution were uncorrelated with the dominant source of energy (the solar-mass-dependent solar flux) on planet Earth.

10.3. The Fermi Paradox

Enrico Fermi posed his famous question "Don't you ever wonder where everybody is?" to Emil Konopinski, Edward Teller, and Herbert York at Los Alamos in 1950 (Horowitz 2002). In its modern version, the Fermi paradox maintains that if other civilizations exist in the Milky Way Galaxy, some must be much older (perhaps by billions of years) than ours; that such civilizations would long ago have developed interstellar travel; that they would then have explored or colonized the Galaxy on a timescale short compared with the Galaxy's lifetime; and that they would therefore be here. But because they are not here, they must not exist (Tarter 2003). The paradox obviously does not hold in a strict logical sense, as each of its assertions is at best a claim of probability (Freitas 1985). In particular, one of its premises is an assertion that has not been unarguably demonstrated. Assuming that an extraterrestrial probe would have a size below 10 m, Freitas (1985) estimated that over 99.999% of heliocentric orbital space and 99.96% of the surface area in the Solar System remained unexplored to the level of resolution that would be required to detect such a probe; these percentages would be somewhat smaller now but not enough so to change the qualitative conclusion. He further asserted, "the assertion that a resident artifact would alert us to its presence is an unwarranted, unsupportable, and untenable assumption."

Whatever the rigor of the Fermi paradox, there have been a wide variety of solutions proposed to solve it (for reviews see Goldsmith 1980, Zuckerman &

Hart 1995, Webb 2002). The challenge to many of these solutions is the large-number assertion: Although this or that explanation might explain the failure of some, even most, civilizations to colonize the Galaxy, the timescale for colonization is putatively so short (Jones 1976, von Hoerner 1978, Tipler 1980) that unless the total number of civilizations in galactic history were quite small, the Galaxy would indeed have been colonized. (The colonization of our Solar System would presumably have been noticed by humans, but one can object even to this claim if the asteroid or Kuiper belt were the colonization venue.) Various practical arguments against galactic spaceflight becoming commonplace have been countered through the invocation of either genetic engineering (Hart 1985) or artificial intelligence in the form of self-replicating and evolving von Neumann machines (von Neumann 1966, Tipler 1980). Counterarguments have been offered (Newman & Sagan 1981).

We only comment that galactic colonization scenarios have shown a faith in exponential reproduction and a lack of attention to what one might call ecological factors, such as the evolution of predation (S.R. Palumbi, private communication) or other behavior that could have the effect of reducing the rate of expansion of a space-faring population. For example, why should self-replicating and evolving von Neumann machines not evolve to prey on one another—the effect of which would be to create a trophic ecology (a food chain) among von Neumann machines and, by standard ecological equations (Maynard Smith 1968), to reduce their rate of population increase and therefore the rate of their spread through the galaxy? There is a danger of mentally endowing such machines with a desired fixed behavior, forgetting the fact that evolving entities often change to suit immediate needs of increased fitness. Then what parameters does one choose in predator-prey modeling to predict accurately the expansion timescale of an evolving galactic ecology of cannibalizing von Neumann machines? It is hard to make such parameter choices with a feeling of confidence.

10.4. The Search for Extraterrestrial Intelligence (SETI)

In the face of the unknowns facing the large-number, anthropic, and Fermi-paradox arguments for the prevalence of intelligent life elsewhere, it is reasonable to adopt an empirical strategy and conduct a scientific search for extraterrestrial technical intelligence (Cocconi & Morrison 1959). This approach has been thoroughly reviewed (Tarter 2001). Here we emphasize that modern strategies, such as the SETI Institute's Project Phoenix, do not assume so-called magic frequencies but rather scan literally billions of microwave frequencies with narrow bandwidths while allowing for frequency drift and rigorously excluding terrestrial interference. Over a decade, Project Phoenix devoted about 460 days of observing time searching the nearest $\sim 10^3$ Sun-like stars. The new Allen Telescope Array (ATA), if funded to completion, should allow 10^5–10^6 stars to be searched, across an even greater frequency range, over a decade of observing at sensitivities comparable to that Phoenix attained at the Arecibo radiotelescope (Tarter 2001, Ekers et al. 2002).

Even the completion of a decade's searching with the ATA, however, will sample $<10^{-5}$ of the stars in our Galaxy.

Though there are good reasons for transmitting civilizations in the Galaxy to favor microwave frequencies within the electromagnetic spectrum, cases can be made for searching at other frequencies as well (Ekers et al. 2002) or for altogether different kinds of interstellar messaging (Tarter 2001), including physical artifacts (Papagiannis 1978, Rose & Wright 2004).

The difficulty in deciphering Mayan texts on Earth—a feat finally accomplished in part because of extant descendants still speaking related languages—is a reminder that deciphering any electromagnetic message that might one day be received could prove enormously difficult (Finney & Bentley 1998).

10.5. Conclusions from Terrestrial Biological Evolution

A final way to assess the prospects for other intelligent life in the universe is to extrapolate from the history of life on Earth. There is a standard set of arguments in the field that have now been repeated for a full century, beginning with Alfred Russel Wallace (1904), the codiscoverer of the theory of evolution, and subsequently revived at intervals since (Simpson 1964, Gould 1989, Mayr 1995, Ward & Brownlee 2000). These authors emphasize the contingency of evolution, how if one were to replay the evolution of animals since the late Precambrian some 600 Mya, the results would likely be very different, and in particular "the chance becomes vanishingly small that anything like human intelligence would grace the replay" (Gould 1989). The evolution of human intelligence, after all, depended on a myriad of contingent factors, not the least of which was the collision of a major asteroid with the Earth 65 Myr ago. The counterarguments are now equally familiar (Sagan 1977, Gould 1985, Conway Morris 2003): convergence is frequently observed in terrestrial evolutionary history, and nature has evolved complex phenomena such as eyesight and flight many times, so that even though any given evolutionary line might seem highly contingent, a large number of parallel paths might lead to the same functional outcome. (Indeed, biological convergence is much more common than the famous examples like sight and flight alone suggest; Conway Morris (2003) includes a "convergences index" that references about 400 evolutionary examples.) To this, in turn, the reply is made that technical intelligence has only evolved once on Earth, so that there are few signs of convergence operating in this realm (Mayr 1995, Diamond 1995). But Gould (1985) questioned whether this conclusion should be extended from one planet to the universe, and others have questioned the premise of the claim. At a minimum, several species of marine mammals, which last shared a common ancestor with our own primate lineage over 90 Myr ago, have developed a level of intelligence that by objective, quantifiable measures is well in excess of that of chimpanzees and slightly in excess of that of *homo habilis*, one of modern humans' tool-using predecessors (Marino 1996).

The latter example hints that progress might be made toward resolving questions of the contingency versus convergence of intelligence if research in the area could

move beyond the past century's qualitative polemics and into the realm of objective quantitative statistical tests based on the fossil record and evolutionary phylogenies. Despite very low levels of funding available for such research, in the past few years, important first steps in the direction of this research program were undertaken. We summarize these in the next section.

11. EVOLUTION OF INTELLIGENCE

To study the evolution of intelligence quantitatively, one needs a reproducible measurement that correlates with what is meant by intelligence, and that can be employed with the fossil record as well as with contemporary organisms. In fact, there is one good such measure that is widely used—the concept of encephalization (Jerison 1955, 1973). Encephalization is typically expressed as a quotient (hence, encephalization quotient, or EQ) that quantifies how much smaller or larger a particular animal's brain is compared to the expected (via a regression over many animals) brain size for an animal of that body size (Marino, McShea & Uhen 2004). Although there are variations in the exact definition, we use Jerison's (1973) definition, e.g., $EQ_{0.67} = $ (brain weight)/$[0.12$ (body weight)$^{0.67}]$, where the subscript designates the exponent of body weight. Animals with $EQ > 1$ are brainier than expected; those with $EQ < 1$ are less brainy than expected for their body size. There is strong evidence that EQ among primates correlates with innovatory behaviors, social learning, and tool use (Reader & Laland 2002; Lefebvre, Reader & Sol 2004); among birds it correlates with behavioral flexibility (Lefebvre et al. 1997). Contemporary humans have the highest EQ currently on the planet at $EQ_{0.67} = 7.1$, meaning that our brain is more than 7 times larger than the typical value for an animal of our body weight.

Interestingly, the next highest EQ values on Earth are those of four dolphin species, with a mean $EQ_{0.67}$ of 4.6 and the highest of the four about 5.0 (Marino, McShea & Uhen 2004). Great apes come in much lower, with a mean around 1.9, about the same as that of the human ancestor *Australopithecus*. Among our more recent ancestors, *Homo erectus* and the earlier *Homo habilis* had $EQ_{0.67}$ values of about 5.3 and 4.3, respectively (Marino 1996). Corresponding to the high EQ values, there is evidence for convergent behavioral abilities between toothed whales (*odontoceti*, which include dolphins) and humans, for example in mirror self-recognition (Reiss & Marino 2001) and intergenerational transmission of behaviors that have been described as cultural (Rendell & Whitehead 2001). Marino (2002) and Conway Morris (2003) argue that toothed whale brain size and behavioral abilities are convergent with those of humans, despite their separate evolutionary histories from over 90 Mya.

These results already suggest that it is too simple to assert that the evolution of human intelligence on Earth is some entirely exceptional phenomenon. But with a sufficiently large database of EQ measurements for fossil whales species, one can further begin to test quantitatively familiar assertions, such as the conventional

wisdom that increases in encephalization should be pervasive across groups and their component lineages because of the selective advantage that encephalization confers (Gould 1988). Marino, McShea & Uhen (2004) have done this analysis, applying statistical tests such as parsimony and maximum likelihood to data for modern and fossil whales going back 50 Myr (Figure 1). Although the overall average level of encephalization has been increasing, at any given time subsequent lineages show both decreases and increases in EQ. Evidently encephalization was not pervasively advantageous across all lineages. The conventional wisdom, when addressed quantitatively, fails to hold. Yet the "bush-like" nature of the evolution of EQ in Figure 1 suggests that evolution may have explored many parallel paths to the high-EQ end of the distribution.

These results are those of only a nascent research program, but they emphasize that there are reproducible, quantitative methods that can now be applied to begin to address long-standing questions about the likelihood of the evolution of intelligence in the universe. Just as studies of microscopic life on Earth inform thinking about the prospects for microorganisms elsewhere, so should rigorous exploration of the evolution of intelligence on Earth inform astrobiologists' thinking about the prospects for intelligence elsewhere. Treating intelligence as a property of the biological universe that can be quantitatively investigated—even though, as with life itself, we do not yet know if it is unique to Earth, rare, or common in the Galaxy—should allow us to move beyond polemics and adapt our thinking to actual data.

12. A POST-HUMAN FUTURE?

Assertions about the nature and capabilities of galactic civilizations often rely heavily on extrapolations from technical intelligence on Earth. For example, many of the Fermi paradox arguments that assume galactic colonization invoke machine intelligence (Tipler 1980) or substantial genetic engineering (Hart 1985). The claim

Figure 1 Mean encephalization quotients ($EQ_{0.67}$) through time for archaeocete and odontocete cetacean species (ancestral whales and toothed whales, respectively). The odontocete superfamily Delphinoidea (dolphins, porpoises, belugas, and narwhals) forms the upper range of odontocete EQ values from the middle Miocene to the present; four species of dolphins with a mean $EQ_{0.67}$ of 4.6 are the most highly encephalized species on the planet after modern humans. For comparison, modern humans and their tool-using ancestors *Homo erectus* and the earlier *Homo habilis* have $EQ_{0.67} = 7.1$, 5.3, and 4.3, respectively; the even earlier *Australopithecus* had an $EQ_{0.67}$ about that of the mean for modern apes, around 1.9 (Marino 1996). EQ expanded toward both higher and lower values within Delphinoidea, suggesting the absence of an overall drive toward higher levels of encephalization for Delphinoidea as a whole. From Marino, McShea & Uhen (2004).
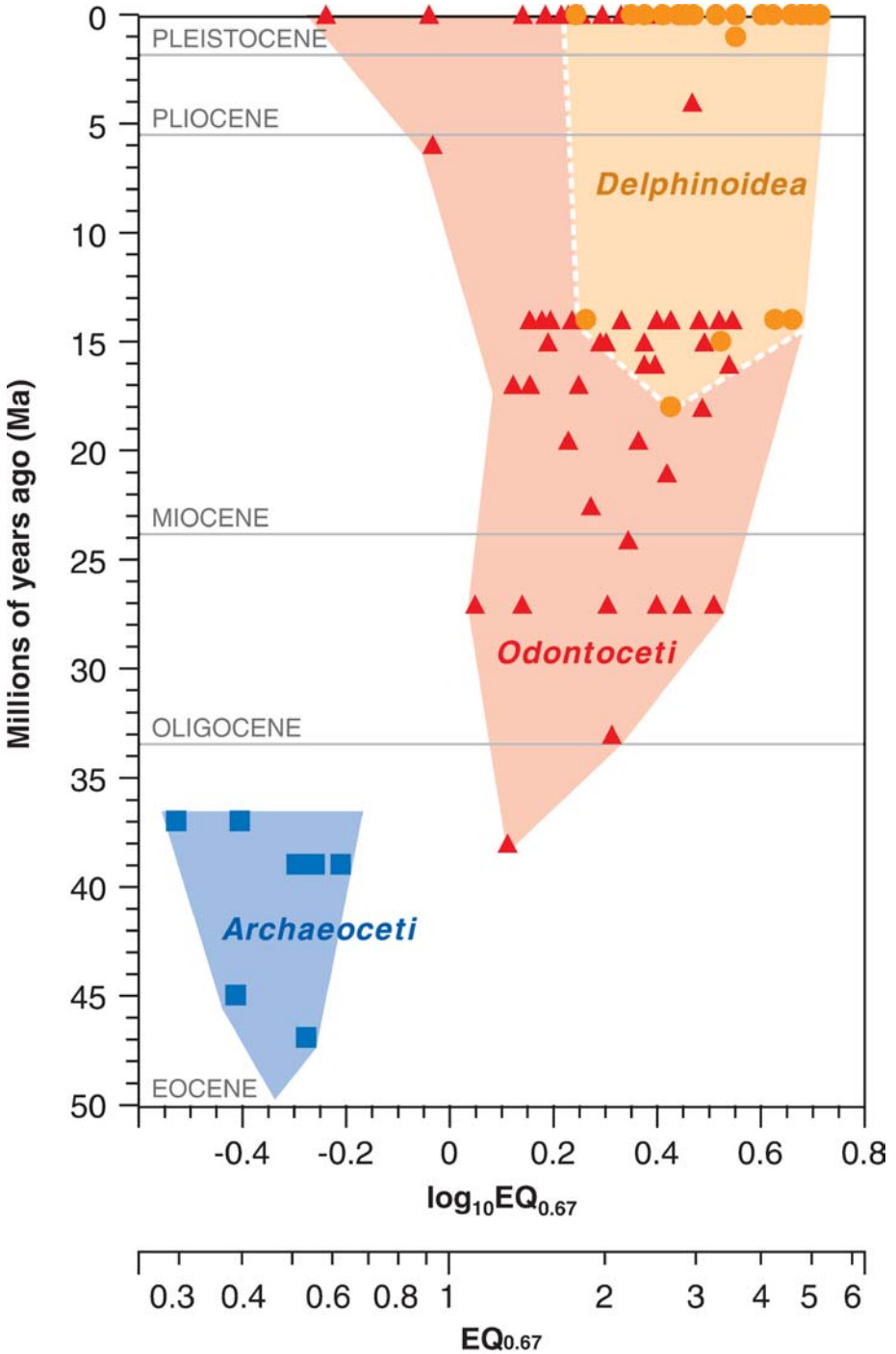
is that the timescale for the one or the other of these to be realized is much shorter than the timescale for the realization of interstellar spaceflight (Hart 1985, Vinge 1993). We should not exaggerate the ease or casualness with which substantial genetic manipulation of human beings will be done, but it is undeniable that basic measures of human bioengineering capability, such as the time or cost required to sequence or synthesize DNA oligomers (Carlson 2003), show that biotechnology is exponentially advancing at a rate as fast or faster than that of Moore's law (Moore 1965) in computing (Figure 2). It is hard to make predictions far past the current exponential lift-off.
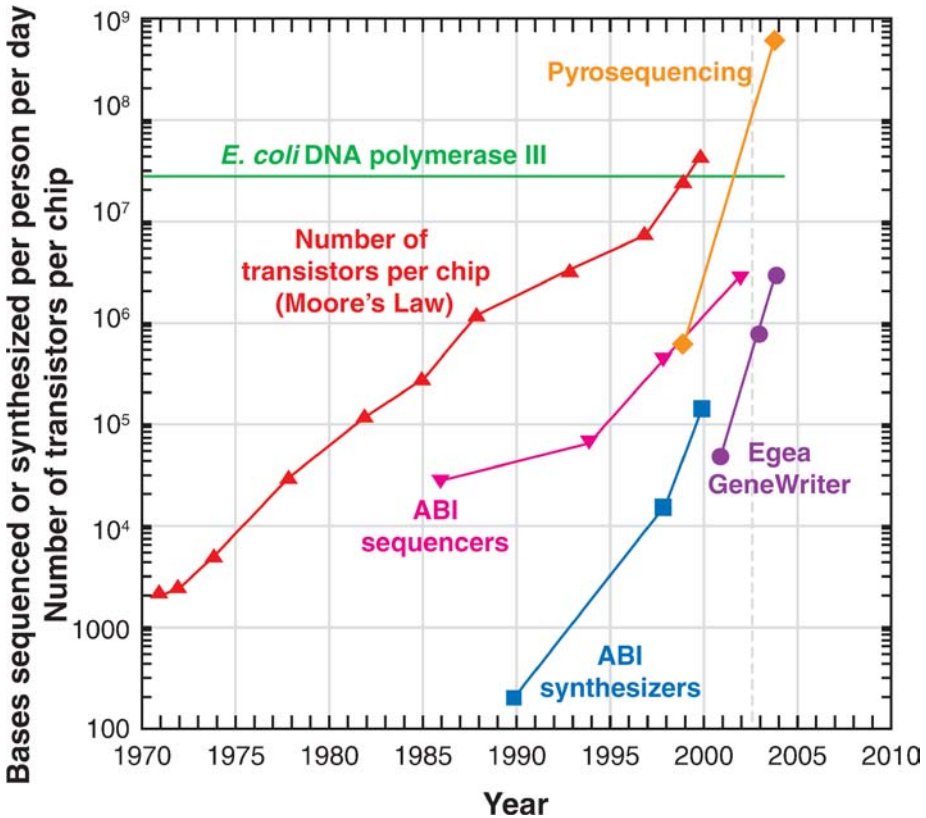
Figure 2   Plot showing DNA synthesis and sequencing productivity through time for a variety of technologies. (ABI is the brand name of Applied Biosystems.) For comparison, the rate at which a single molecule of DNA polymerase III in the bacterium *E. coli* replicates DNA is shown. All biological and biotechnological data are referenced to an eight-hour day. Synthesis and sequencing productivity is now increasing as fast or faster than Moore's Law (*upwards triangles*). From Carlson (2003).

It is commonplace to argue that computer intelligence is merely decades away, but there remain fundamental arguments that digital computers will never be intelligent (Searle 1984). Nevertheless, such machines may become so numerically powerful that they can strongly mimic an autonomous intelligence [see Searle (1984) for why it is unconvincing to make the familiar positivistic claim that this is "the same thing" as their being intelligent], or an altogether different approach to artificial intelligence that sidesteps the syntax/semantics dichotomy facing digital computers may be found. In any event, whether through biological engineering of the human intellect, advances in human/machine interfacing, or the invention of autonomous machine intelligence, some observers (Bernal 1929, Vinge 1993) argue that we are about to enter a realm where technical intelligence (and its own subsequent directed evolution) advances so quickly that it will be impossible for contemporary human beings to play a significant role in the resulting subsequent civilization. It may prove generally true that there is only a brief interval during which a species is technically intelligent yet still retains its biologically evolved form. If so, we should expect that any civilization with which we make contact through SETI or otherwise is unlikely to resemble its biological predecessor species.

None of this is to advocate the substantial engineering of the human species; there may be reasons to dread this outcome (Bernal 1929, Vinge 1993, Joy 2000, Fukuyama 2002, Rees 2003). Moreover, well before it permits the reengineering of the human species, biotechnology will put great power for potential terrorist acts into the hands of small groups of the technically competent, and we do not have adequate models from Cold War arms control or nuclear nonproliferation for how we are to prevent disaster in this new world (Chyba 2002, Chyba & Greninger 2004). Simultaneously with our rapidly increasing sophistication in searching for extraterrestrial life, humanity faces extraordinary challenges driven by the same underlying explosion in our technical prowess. We began this essay with the statement that astrobiology is "the study of the living universe." If so, then the discipline must also speak to the future of human civilization, a thing uniquely precious regardless of whether it is terribly alone or part of a vast biological universe.

The *Annual Review of Astronomy and Astrophysics* is online at
http://astro.annualreviews.org

LITERATURE CITED

Acuna MH, Connerney JEP, Ness NF, Lin RP, Mitchell D, et al. 1999. *Science* 284:790–94

Altman S, Baer MF, Bartkiewicz M, Gold H, Guerrier-Takada C, et al. 1989. *Gene* 82:63–64

Anderson JD, Schubert G, Jacobson RA, Lau EL, Moore WB, Sjogren WL. 1998. *Science* 281:2019–22

Aristotle. *De Anima*. Transl. JA Smith, 1941, in *The Basic Works of Aristotle*, ed. R McKeon, pp. 533–603. New York: Random House. 1487 pp.

Aristotle. *De Caelo*. Transl. JL Stocks, 1941, in *The Basic Works of Aristotle*, ed. R McKeon, pp. 395–466. New York: Random House. 1487 pp.

Arrhenius S. 1903. *Die Umschau* 7:481. Transl. D Goldsmith, 1980, in *The Quest for Extraterrestrial Life*, ed. D Goldsmith, pp. 32–33. Mill Valley, CA: Univ. Science Books. 308 pp.

Balázs BA. 1986. *Acta Astronaut.* 13:21

Balázs BA. 1988. In *Bioastronomy: The Next Steps*, ed. G Marx, p. 61. London: Kluwer

Barrow JD, Tipler FJ. 1986. *The Anthropic Cosmological Principle*. New York: Oxford Univ. Press. 706 pp.

Benner SA, Devine KG, Matveeva LN, Powell DH. 2000. *Proc. Natl. Acad. Sci. USA* 97:2425–30

Benner SA, Ricardo A, Carrigan MA. 2004. *Curr. Opin. Chem. Biol.* 8:672–89

Bernal JD. 1929 (1969). *The World, the Flesh, and the Devil*. Bloomington: Univ. Indiana Press. 81 pp.

Bernal JD. 1952. Lecture to the British Interplanetary Society, described in Slater AE. *J. Br. Interplanet. Soc.* 12:114–18

Beukes NJ, Lowe DR. 1989. *Sedimentology* 36:383–97

Bennett CL. 2005. *Science* 307:879–84

Biemann K, Oro J, Toulmin P III, Orgel LE, Nier AO, et al. 1977. *J. Geophys. Res.* 82:4641–58

Blum HF. 1962. *Time's Arrow and Evolution*. New York: Harper & Bros. 220 pp. 2nd ed.

Bondi H, Gold T. 1948. *MNRAS* 108:252–70

Bostrom N. 2002. *Anthropic Bias: Observational Selection Effects in Science and Philosophy*. New York: Routledge. 224 pp.

Brasier MD, Green OR, Jephcoat AP, Kleppe AK, Van Kranendonk MJ, et al. 2002. *Nature* 416:76–81

Brocks JJ, Logan GA, Buick R, Summons RE. 1999. *Science* 285:1033–36

Butler RP, Vogt SS, Marcy G, Fischer D, Wright JT, et al. 2004. *Astrophys. J.* 617:580–88

Carlson R. 2003. *Biosecurity Bioterrorism* 1:203–14

Carroll SM. 2001. *Living Rev. Relativ.* 4:1–50

Carter B. 1974. In *Confrontation of Cosmological Theories with Observational Data*, ed. MS Longair, pp. 291–98. Dordrecht: Reidel

Carter B. 1983. *Philos. Trans. R. Soc. London Ser. A* 310:347–63

Cassen P, Reynolds RT, Peale SJ. 1979. *Geophys. Res. Lett.* 6:731–34

Cassen P, Reynolds RT, Peale SJ. 1980. *Geophys. Res. Lett.* 7:987–88

Cech TR. 1993. *Gene* 135:33–36

Chapelle FH, O'Neill K, Bradley PM, Methé BA, Ciufo S, et al. 2002. *Nature* 415:312–15

Chyba CF. 1997. *Nature* 385:201

Chyba CF. 2002. *Foreign Aff.* 81(3):122–36

Chyba CF. 2003. In *Space Policy in the 21st Century*, ed. WH Lambright, pp. 198–231. Baltimore: Johns Hopkins Univ. Press. 283 pp.

Chyba CF, Greninger AL. 2004. *Survival* 46:143–62

Chyba CF, Hand KP. 2001. *Science* 292:2026–27

Chyba CF, McDonald GD. 1995. *Annu. Rev. Earth Planet. Sci.* 23:215–49

Chyba CF, Phillips CB. 2001. *Proc. Natl. Acad. Sci. USA* 98:801–4

Chyba CF, Phillips CB. 2005. See Sullivan & Baross 2005. In press

Chyba CF, Sagan C. 1992. *Nature* 355:125–32

Chyba CF, Thomas PJ, Brookshaw L, Sagan C. 1990. *Science* 249:366–73

Chyba CF, Whitmire DP, Reynolds R. 2000. In *Protostars and Planets IV*, ed. V Mannings, AP Boss, SS Russell, pp. 1365–93. Tucson: Univ. Ariz. Press

Clark DH, McCrea WH, Stephenson FR. 1977. *Nature* 265:318–19

Cleland CE, Chyba CF. 2002. *Orig. Life Evol. Biosph.* 32:387–93

Cleland CE, Chyba CF. 2005. See Sullivan & Baross 2005. In press

CNES. 2005. http://smsc.cnes.fr/COROT/GP_science.htm

Cocconi G, Morrison P. 1959. *Nature* 184:844

Colgate S. 1968. *Can. J. Phys.* 46:5476

Conway Morris S. 2003. *Life's Solution: Inevitable Humans in a Lonely Universe*. Cambridge: Cambridge Univ. Press. 464 pp.

Copernicus N. 1543. *De Revolutionibus Orbium Caelestium*. Transl. CG Wallis, 1995, *On the Revolutions of Heavenly Spheres*. Amherst: Prometheus Books. 336 pp.

Crutzen PJ. 2002. *Nature* 415:23

Darwin C. 1871. Letter to Hooker. In *Search for the Universal Ancestors* 1985, ed. H Hartman, JG Lawless, P Morrison, pp. 12–13. NASA SP-477

Davies RE. 1988. *Acta Astron.* 17:129–35

da Vinci L. 1513. *Il Codice Arundel*, No. 263, fol. 57r. Transl. E MacCurdy, 2003. *The Notebooks of Leonardo da Vinci*. Old Saybrook, Conn: Konecky & Konecky. 1180 pp.

de Duve C, Miller SL. 1991. *Proc. Natl. Acad. Sci. USA* 88:10014–17

Deamer DW. 1997. *Microbiol. Mol. Biol. Rev.* 61:239–61

Deamer DW, Oró J. 1980. *Biosystems* 12:167–75

Deamer DW, Pashley RM. 1989. *Orig. Life Evol. Biosph.* 19:21–38

Diamond J. 1995. See Zuckerman & Hart 1995, pp. 157–64

Dick SJ. 1996. *The Biological Universe*. Cambridge: Cambridge Univ. Press. 578 pp.

Doolittle WF. 1999. *Science* 284:2124–28

Drake F, Sobel D. 1992. *Is Anyone Out There?* New York: Delacorte Press. 272 pp.

Dreyer JLE. 1953. *A History of Astronomy from Thales to Kepler*. London: Dover. 437 pp.

Dworkin JP, Deamer DW, Sandford SA, Allamandola LJ. 2001. *Proc. Natl. Acad. Sci. USA* 98:815–19

Dyson F. 1985. *Origins of Life*. Cambridge: Cambridge Univ. Press

Ehrenfreund P, Irvine W, Becker L, Blank J, Brucato JR, et al. 2002. *Rep. Prog. Phys.* 65: 1427–87

Ekers RD, Cullers DK, Billingham J, Scheffer LK, eds. 2002. *SETI 2020*. Mountain View, CA: SETI Press. 549 pp.

Eur. Space Agency (ESA). 2005a. http://www.esa.int/SPECIALS/Cassini-Huygens/

Eur. Space Agency (ESA). 2005b. http://sci.esa.int/science-e/www/area/index.cfm?fareaid=28

Exoplanets. 2005. http://www.exoplanets.org

Fedo CM, Whitehouse MJ. 2002. *Science* 296:1448–52

Feinberg G, Shapiro R. 1980. *Life Beyond Earth*. New York: Morrow

Finney B, Bentley J. 1998. *Acta Astronaut.* 42: 691–96

Fischer DA, Butler RP, Marcy GW, Vogt SS, Henry GW. 2003. *Astrophys. J.* 590:1081–87

Fischer DA, Valenti J, Marcy G. 2004. In *Stars as Suns: Activity, Evolution and Planets*, ed. AK Dupree, AO Benz, pp. 1–12. Dordrecht: Kluwer

Formisano V, Atreya S, Encrenaz T, Ignatiev N, Giuranna M. 2004. *Science* 306:1758–61

Freitas RA. 1985. *Icarus* 62:518–20

Fukuyama F. 2002. *Our Posthuman Future*. New York: Farrar, Straus & Giroux. 256 pp.

Gaidos EJ, Nealson KH, Kirschvink JL. 1999. *Science* 284:1631–33

Garcia-Ruiz JM, Hyde ST, Carnerup AM,

Christy AG, Van Kranendonk MJ, Welham NJ. 2003. *Science* 302:1194–97

Gilbert W. 1986. *Nature* 319:618

Glavin DP, Schubert M, Botta O, Kminek G, Bada JL. 2001. *Earth Planet Sci. Lett.* 185:1–5

Gogarten JP, Doolittle WF, Lawrence JG. 2002. *Mol. Biol. Evol.* 19:2226–38

Gold T. 1992. *Proc. Natl. Acad. Sci. USA* 89:6045–49

Goldsmith D, ed. 1980. *The Quest for Extraterrestrial Life: A Book of Readings.* Mill Valley, CA: Univ. Sci. Books. 308 pp.

Gonzalez G, Brownlee D, Ward P. 2001. *Icarus* 152:185–200

Gonzalez GJ, Richards JW. 2004. *The Privileged Planet.* Washington, DC: Regnery. 444 pp.

Gott JR. 1993. *Nature* 363:315–19

Gould SJ. 1985. *The Flamingo's Smile: Reflections in Natural History.* New York: Norton. 476 pp.

Gould SJ. 1988. *J. Paleontol.* 62:319–29

Gould SJ. 1989. *Wonderful Life: The Burgess Shale and the Nature of History.* New York: Norton. 347 pp.

Griffith CA, Hall JL, Geballe TR. 2000. *Science* 290:509–13

Griffith CA, Owen T, Geballe TR, Rayner J, Rannou P. 2003. *Science* 300:628–30

Grotzinger J, Rothman DH. 1996. *Nature* 383:423–25

Haldane JBS. 1929. *Ration. Annu.* 143:3–10

Haldane JBS. 1954. *New Biol.* 16:12–27

Hargreaves WR, Mulvihill SJ, Deamer DW. 1977. *Nature* 266:78–80

Hart MH. 1985. In *Interstellar Migration and the Human Experience*, ed. BR Finney, EM Jones, pp. 278–91. Los Angeles: Univ. Calif. Press. 354 pp.

Head J, Mustard JF, Kreslavsky MA, Milliken RE, Marchant DR. 2003. *Nature* 426:797

Henderson LJ. 1913. *The Fitness of the Environment.* New York: Macmillan. 317 pp.

Horneck G, Bücker H, Reitz G. 1994. *Adv. Space Res.* 14:41–45

Horneck G, Eschweiler U, Reitz G, Wehner J,

Willimek R, Strauch K. 1995. *Adv. Space Res.* 16:105–11

Horowitz NH. 1986. *To Utopia and Back: The Search for Life in the Solar System.* New York: Freeman. 168 pp.

Horowitz P. 2002. Appendix J. See Ekers et al. 2002, pp. 373–74

Howard AD. 2002. *Nature* 419:350–51

Hoyle F. 1948. *MNRAS* 108:372–82

Hu W, Dodelson S. 2002. *Annu. Rev. Astron. Astrophys.* 40:171–216

Huber C, Wächtershäuser G. 1997. *Science* 276:245–47

Huber C, Wächtershäuser G. 1998. *Science* 281:670–72

Huheey JE, Keiter EA, Keiter RL. 1993. *Inorganic Chemistry: Principles of Structure and Reactivity*, pp. 861–63. New York: HarperCollins. 964 pp.

Hutchison CA, Peterson SN, Gill SR, Cline RT, White O, et al. 1999. *Science* 286:2165–69

IAU. 2004. *International Astronomical Union.* http://www.ifa.hawaii.edu/~meech/iau/

James KD, Ellington AD. 1995. *Orig. Life Evol. Biosph.* 25:515–30

Jerison HJ. 1955. *Science* 121:447–49

Jerison HJ. 1973. *Evolution of the Brain and Intelligence.* New York: Academic

Jet Propulsion Lab. (JPL). 2005. http://planetquest.jpl.nasa.gov/TPF/tpf_index.html

Jones EM. 1976. *Icarus* 28:421–22

Joshi MM, Haberle RM, Reynolds RT. 1997. *Icarus* 129:450–65

Joy B. 2000. *Wired.* http://www.wired.com/wired/archive/8.04/joy_pr.html

Joyce GF. 1994. In *Origins of Life: The Central Concepts*, ed. DW Deamer, GR Fleischaker, p. xi. Boston: Jones & Bartlett. 431 pp.

Kahn R. 1985. *Icarus* 62:175–90

Kargel JS. 2004. *Mars: A Warmer Wetter Planet.* New York: Springer-Verlag. 557 pp.

Kasting JF, Catling D. 2003. *Annu. Rev. Astron. Astrophys.* 41:429–63

Kerr RA. 2005. *Science* 307:330–31

Kivelson MG, Khurana KK, Russell CT, Volwerk M, Walker RJ, et al. 2000. *Science* 289:1340–43

Klein HP. 1978. *Icarus* 34:666–74

Knoll A. 2003. *Life on a Young Planet*. Princeton: Princeton Univ. Press

Koshland DE. 2002. *Science* 295:2215–16

Krasnopolsky VA, Maillard JP, Owen TC. 2004. *Icarus* 172:537–47

Kuhn TS. 1957. *The Copernican Revolution*. Cambridge, MA: Harvard Univ. Press. 297 pp.

Lafleur LJ. 1941. *Leafl. Astron. Soc. Pac.* 143: 333–40

Laskar J, Joutel F, Robutel P. 1993. *Nature* 361:615–17

Laskar J, Levrard B, Mustard JF. 2002. *Nature* 419:375–77

Laskar J, Robutel P. 1993. *Nature* 361:608–12

Lawrence JG, Ochman H. 1998. *Proc. Natl. Acad. Sci. USA* 95:9413–17

Lazcano A, Miller SL. 1994. *J. Mol. Evol.* 39: 546–54

Lederberg J. 1960. *Science* 132:393–98

Lefebvre L, Reader SM, Sol D. 2004. *Brain Behav. Evol.* 63:233–46

Lefebvre L, Whittle P, Lascaris E, Finkelstein A. 1997. *Anim. Behav.* 53:549–60

Lepland A, van Zuilen MA, Arrhenius G, Whitehouse MJ, Fredo CM. 2005. *Geology* 33:77–79

Leslie J. 1996. *Universes*. London: Routledge. 228 pp.

Linde A. 1990. *Particle Physics and Inflationary Cosmology*. New York: CRC Press. 362 pp.

Linde AD. 1986. *Phys. Lett. B* 175:395–400

Lineweaver CH, Fenner Y, Gibson BK. 2004. *Science* 303:59–62

Lissauer JJ, Dones L, Ohtsuki K. 2000. In *Origin of the Earth and Moon*, eds. RM Canup, K Righter, pp. 101–12. Tucson: Univ. Arizona.

Livio M. 1999. *Astrophys. J.* 511:429–31

Lodders K, Fegley B. 1998. *The Planetary Scientist's Companion*. Oxford: Oxford Univ. Press. 371 pp.

Lovelock JE. 2003. *Nature* 426:769–70

Lunine JI, Stevenson DJ, Yung YL. 1983. *Science* 222:1229–30

Maher KA, Stevenson DJ. 1988. *Nature* 331: 612–14

Malin MC, Edgett KS. 2000. *Science* 288: 2330–35

Marcy G, Butler RP, Fischer D, Vogt SS, Lissauer JJ, Rivera EJ. 2001. *Astrophys. J.* 556:296–301

Margulis L. 1999. *The Symbionic Planet*. London: Phoenix

Marino L. 1996. *Evol. Anthropol.* 5:81–85

Marino L. 2002. *Brain Behav. Evol.* 59:21–32

Marino L, McShea DW, Uhen MD. 2004. *Anat. Rec. Part A* 281A:1247–55

Marochnik L, Mukhin LM. 1986. In *The Problem of the Search for Life in the Universe*, *Proc. Conf. SETI, Tallin, Estonia, USSR, Dec. 7–11, 1981*, ed. VA Ambartsumyan, NS Kardashev, VS Troitskii, pp. 41–46. Moscow: Nauka

Mars Explor. Rovers (MER). 2004. http://mars.jpl.nasa.gov

Marshall E. 2002. *Science* 298:1701

Maynard Smith J. 1968. *Mathematical Ideas in Biology*. Cambridge: Cambridge Univ. Press. 152 pp.

Mayr E. 1995. See Zuckerman & Hart 1995, pp. 152–56

Mazur P. 1980. *Orig. Life Evol. Biosph.* 10: 137–59

McCollom TM. 1999. *J. Geophys. Res.* 104: 30729–42

McDonough W, Braungart M. 2002. *Cradle to Cradle, Remaking the Way We Make Things*. New York: North Point Press. 193 pp.

McKay CP, Toon OB, Kasting JF. 1991. *Nature* 352:489–96

Melia F, Falcke H. 2001. *Annu. Rev. Astron. Astrophys.* 39:309–52

Mileikowsky C, Cucinotta FA, Wilson JW, Gladman B, Horneck G, et al. 2000. *Icarus* 145:391–427

Miller SL. 1953. *Science* 117:528–29

Miller SL, Urey HC. 1959. *Science* 130:245–51

Mojzsis SJ, Arrhenius G, McKeegan KD, Harrison TM, Nutman AP, Friend CRL. 1996. *Nature* 384:55–59

Moorbath S. 2005. *Nature* 434:155

Moore G. 1965. *Electronics* 38:114–17

Morrison D. 2005. *Sci. Global Security*. In press

Mumma MJ, Novak RE, DiSanti MA, Bonev BP. 2003. *Bull. Am. Astron. Soc.* 35: 937

Narlikar JV, Padmanabhan T. 2001. *Annu. Rev. Astron. Astrophys.* 39:211–48

NASA ARC. 2004. http://www.kepler.arc.nasa.gov/summary.html

NASA Astrobiol. Inst. (NAI). 2004. http://www.nai.arc.nasa.gov/institute/about_nai.cfm#astrobiology

NASA JPL. 2004. http://mars.jpl.nasa.gov/overview/

National Research Council. 1992. *Biological Contamination of Mars*. Washington, DC: Natl. Acad. Press

National Research Council. 1997. *Mars Sample Return*. Washington, DC: Natl. Acad. Press

National Research Council. 2000. *Preventing the Forward Contamination of Europa*. Washington, DC: Natl. Acad. Press

National Research Council. 2005. *Preventing the Forward Contamination of Mars*. Washington, DC: Natl. Acad. Press. In press

Nealson KH. 1997. *J. Geophys. Res.* 102: 23675–86

Newman WI, Sagan C. 1981. *Icarus* 46:293–327

Newton IS. 1686. *Philosophiae Naturalis Principia Mathematica*. Transl. A Motte, 1729, in *Principia*, *Vol. Two: The System of the World*, ed. F Cajori. Berkeley: Univ. Calif. Press. 680 pp.

Nisbet EG, Sleep NH. 2001. *Nature* 409:1083–91

Ojakangas GW, Stevenson DJ. 1989. *Icarus* 81:220–41

Oparin AI. 1924. *Proiskhozhdenie Zhizny*. Moscow: Izd. Moskovshii Rabochii. 1994. In *Origins of Life: The Central Concepts*, ed. DW Deamer, GR Fleischaker, pp. 31–71. Boston: Jones & Bartlett. 431 pp.

Oreskes N. 2003. *Plate Tectonics*. Boulder, CO: Westview. 424 pp.

Orgel LE. 1998. *Orig. Life Evol. Biosph.* 28:91–96

Oró J. 1961. *Nature* 191:1193–94

Pace NR. 1997. *Science* 276:734–40

Palmer M, Bernhardt E, Chornesky E, Collins S, Dobson A, et al. 2004. *Science* 304:1251–52

Palumbi SR. 2001. *Science* 293:1786–90

Papagiannis M. 1978. *Q. J. R. Astron. Soc.* 19: 277–79

Pappalardo RT, Belton MJS, Breneman HH, Carr MH, Chapman CR, et al. 1999. *J. Geophys. Res.* 104: 24015–55

Payne CH. 1925. *Stellar Atmospheres*, Harvard Obs. Monogr. No. 1, pp. 177–89, Cambridge, MA

Pennisi E. 1999. *Science* 284:1305–7

Pierazzo E, Chyba CF. 1999. *Meteorit. Planet. Sci.* 34:909–18

Pierazzo E, Chyba CF. 2001. *Icarus* 157:120–27

Podolak M, Prialnik D. 1997. See Thomas et al. 1997, pp. 259–72

Porco CC, Baker E, Barbara J, Beurle K, Brahic A, et al. 2005. *Nature* 434:159–68

Rauf T, Nikitin MB, Rissanen J, eds. 2000. *Inventory of International Nonproliferation Organizations and Regimes*, pp. 138–42. Monterey, CA: Cent. Nonprolif. Stud. 256 pp.

Reader SM, Laland KN. 2002. *Proc. Natl. Acad. Sci. USA* 99:4436–41

Rees M. 2001. *Our Cosmic Habitat*. Princeton: Princeton Univ. Press. 205 pp.

Rees M. 2003. *Our Final Hour*. New York: Basic Books. 228 pp.

Reiss D, Marino L. 2001. *Proc. Natl. Acad. Sci. USA* 98:5937–42

Rendell L, Whitehead H. 2001. *Behav. Brain Sci.* 24:309–82

Rieke GH, Su KYL, Stansberry JA, Trilling D, Bryden G, et al. *Astrophys. J.* 620:1010–26

Rose C, Wright G. 2004. *Nature* 431:47–49

Rosing MT. 1999. *Science* 283:674–76

Rosing MT, Frei R. 2004. *Earth Planet. Sci. Lett.* 217:237–44

Ruse M. 1985. In *Extraterrestrials: Science and Alien Intelligence*, ed. E Regis, pp. 43–78. Cambridge: Cambridge Univ. Press. 278 pp.

Sagan C. 1970. *Encycl. Br.* 22:964–81 (Reprinted 1998)

Sagan C, ed. 1973. *Communication with Extraterrestrial Intelligence* (*CETI*). Cambridge, MA: MIT Press. 428 pp.

Sagan C. 1974. *Orig. Life Evol. Biosph.* 5:497–505

Sagan C. 1977. *The Dragons of Eden*. New York: Random House. 271 pp.

Sagan C. 1996. In *Circumstellar Habitable Zones*, ed. LR Doyle, pp. 3–14. Menlo Park, CA: Travis House

Sagan C, Thompson WR, Khare BN. 1992. *Acc. Chem. Res.* 25:286–92

Santos NC, Israelian G, Mayor M, Rebolo R, Udry S. 2003. *Astron. Astrophys.* 398:363–76

Santos NC, Bouchy F, Mayor M, Pepe F, Queloz D, et al. 2004. *Astron. Astrophys.* 426:L19–23

Schidlowski M. 1988. *Nature* 333:313–18

Schopf JW. 1993. *Science* 260:640–46

Schopf JW, Kudryavtsev AB, Agresti DG, Wdowiak TJ, Czaja AD. 2002. *Nature* 416: 73–76

Schopf JW, Packer BM. 1987. *Science* 237:70–73

Schrödinger E. 1945. *What Is Life?* Cambridge: Cambridge Univ. Press. 91 pp.

Schulze-Makuch D, Irwin LN. 2004. *Life in the Universe: Expectations and Constraints*. New York: Springer-Verlag. 172 pp.

Searle J. 1984. *Minds, Brains and Science*. London: BBC. 102 pp.

Segre D, Deamer DW, Lancet D. 2001. *Orig. Life Evol. Biosph.* 31:119–45

Shapiro R. 1988. *Orig. Life Evol. Biosph.* 18: 71–85

Shklovskii I, Sagan C. 1966. *Intelligent Life in the Universe*. New York: Dell

Sigurdsson S, Richer HB, Hansen BM, Stairs IH, Thorsett SE. 2003. *Science* 301:193–96

Simpson GG. 1964. *Science* 143:769–75

Sleep NH, Zahnle KJ, Kasting JF, Morowitz HJ. 1989. *Nature* 342:139–42

Solomatov VS. 2000. In *Origin of the Earth and Moon*, ed. RM Canup, K Righter, pp. 323–38. Tucson: Univ. Ariz. Press. 555 pp.

Squyres SW, Arvidson RE, Bell JF III, Bruckner J, Cabrol NA, et al. 2004a. *Science* 305:794–800

Squyres SW, Grotzinger JP, Arvidson RE, Bell JF, Calvin W, et al. 2004b. *Science* 306:1709–14

Stevenson DJ. 1999. *Nature* 400:32

Stribling R, Miller SL. 1987. *Orig. Life* 17:261–73

Struve O. 1955. *Sky Telesc.* 14:137–46

Sullivan W, Baross J, eds. 2005. *Planets and Life: The Emerging Science of Astrobiology*. Cambridge: Cambridge Univ. Press. In press

Summons RE, Jahnke LL, Hope JM, Logan GA. 1999. *Nature* 400:554–57

Swineburne R. 1990. In *Physical Cosmology and Philosophy*, ed. J Leslie, pp. 154–73. New York: Macmillan. 277 pp.

Tarter J. 2001. *Annu. Rev. Astron. Astrophys.* 39:511–48

Tarter J. 2003. *Science* 299:46–47

Thomas PJ, Chyba CF, McKay CP, eds. 1997. *Comets and the Origin and Evolution of Life*. New York: Springer-Verlag. 296 pp.

Thompson WR, Sagan C. 1992. *Proc. Symp. on Titan, Toulouse, Fr, Sept. 9–12, 1991*, ESA SP-338

Tian F, Toon OB, Paulov AA, De Sterck H. 2005. *Science* 308:1014–17

Tipler FJ. 1980. *Q. J. R. Astron. Soc.* 21:267–81

Touma J. 2000. In *Origin of the Earth and Moon*, eds. RM Canup, K Righter, pp. 165–178. Tucson: Univ. Arizona

Touma J, Wisdom J. 1993. *Science* 259:1294–97

Trimble V. 1995. In *Extraterrestrials: Where Are They?* ed. B Zuckerman, MH Hart, pp. 184–91. Cambridge: Cambridge Univ. Press. 239 pp. 2nd ed.

Turcotte DL, Schubert G. 1982. *Geodynamics*. New York: Wiley. 450 pp.

Ueno Y, Yurimoto H, Yoshioka H, Komiya T, Maruyama S. 2002. *Geochem. Cosmochim. Acta* 66:1257–68

Ulanowicz RE, Hannon RM. 1987. *Proc. R. Soc. London Ser. B* 232:181–92

Van Dover CL. 2000. *The Ecology of Deep-Sea Hydrothermal Vents*. Princeton: Princeton Univ. Press

van Zuilen MA, Lepland A, Arrhenius G. 2002. *Nature* 418:627–30

Vinge V. 1993. In *VISION-21 Symp.*, NASA Conf. Publ. 10129, pp. 11–22

von Hoerner S. 1978. *Naturwissenschaften* 65: 553–57

von Neumann J. 1966. *Theory of Self-Reproducing Automata*. Urbana: Univ. Ill. Press

Wächtershäuser G. 1988. *Microbiol. Rev.* 52: 452–84

Wächtershäuser G. 1990. *Proc. Natl. Acad. Sci. USA* 87:200–4

Wallace AR. 1904. *Man's Place in the Universe*. London: Chapman & Hall. 4th ed.

Walsh MM, Lowe DR. 1985. *Nature* 314:530–32

Ward PD, Brownlee D. 2000. *Rare Earth: Why Complex Life is Uncommon in the Universe*. New York: Copernicus. 333 pp.

Webb S. 2002. *Where Is Everybody?* New York: Copernicus. 288 pp.

Weber AL. 1998. *Orig. Life Evol. Biosph.* 28: 259–70

Weber AL. 2000. *Orig. Life Evol. Biosph.* 30: 33–43

Weinberg S. 1983. *The First Three Minutes*. London: Fontana. 2nd ed.

Weiss BP, Yung Y, Nealson KH. 2000. *Proc. Natl. Acad. Sci. USA* 97:1395–99

Wetherill GW. 1994. *Astrophys. Space Sci.* 212:23–32

Whitman WB, Coleman DC, Wiebe WJ. 1998. *Proc. Natl. Acad. Sci. USA* 95:6578–85

Wilks ME, Nisbet EG. 1985. *Can. J. Earth Sci.* 22:792–99

Wills C, Bada JL. 2000. *The Spark of Life, Darwin and the Primeval Soup*. Cambridge, MA: Perseus

Woese C. 1987. *Microbiol. Mol. Biol. Rev.* 51: 221–71

Woese C. 1998. *Proc. Natl. Acad. Sci. USA* 95: 6854–59

Zuckerman B, Hart MH, eds. 1995. *Extraterrestrials: Where Are They?* Cambridge: Cambridge Univ. Press. 239 pp. 2nd ed.