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## ASTROBIOLOGY: The Study of the Living Universe

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■ **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 planetary 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

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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<sup>a22</sup>–415<sup>b2</sup>). 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)<sup>1</sup>]. All the proposed definitions face problems, often in the form of robust counter-examples

<sup>1</sup>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.



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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 nonpolar liquid, in this sense just the opposite of that for life on Earth. Such speculations (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<sub>4</sub>) and ethane (C<sub>2</sub>H<sub>6</sub>) 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<sub>4</sub> 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 to be conducted 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 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<sup>2</sup>) 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 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).

<sup>2</sup>Organic molecules are molecules based on carbon that contain hydrogen or nitrogen and possibly other atoms.

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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 hodgepodge” (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

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particular, because of this selection effect we cannot validly apply the Copernican 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).

Non-tautological responses to the fine-tuning puzzle currently 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 Baláz (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.<sup>3</sup> After removing observational bias, they find that the probability of finding a  $< 18 M_{\text{Jup}}$  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

<sup>3</sup>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.





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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<sub>2</sub> and H<sub>2</sub>O 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<sub>2</sub> 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<sub>2</sub>O 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<sub>2</sub> 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<sub>2</sub> 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 orbital 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  $3 \text{ m s}^{-1}$ , 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



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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<sub>4</sub> by methanogens and O<sub>2</sub> 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 greatly 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<sub>2</sub> cycle (Kasting & Catling 2003) and probably greatly reducing the surface availability of biologically useful sources of chemical disequilibria to a very low level (Weiss, Yung & Neelson 2000).

Many geologically young features observed on the martian surface may have been caused by changes in solar insolation over time. Milankovitch (after 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



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### 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  $\sim 10\text{--}30$  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  $1000\text{ kg m}^{-3}$  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 ( $\sim 94$  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  $\text{CH}_4$  the second most abundant constituent. Solar ultraviolet photolysis

irreversibly destroys CH<sub>4</sub>, 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 ~800 m thick should cover the surface (Griffith et al. 2003). The persistence of CH<sub>4</sub> 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 (~10<sup>8</sup> 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 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<sub>4</sub> 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 no question that viable microorganisms in spacecraft interiors will survive the cruise from Earth to either Mars (cruise time <1 year) or Europa (cruise time ~3 years). Spores of *Bacillus subtilis* protected against solar radiation survived one year at the ~25% level and six years at the ~1% level on the European Retrieval 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,





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





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reactions to provide an entropically favored way to produce organic molecules. The resulting pyrite ( $\text{FeS}_2$ ) 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.



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The resulting phylogenetic<sup>10</sup> 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

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<sup>10</sup>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,<sup>11</sup> 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,

<sup>11</sup>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.



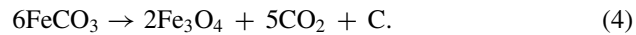




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biosignature.<sup>14</sup> The formation of the graphite, in this scenario, would have resulted from metamorphosed carbonaceous material originally derived from microbial life.

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  $\delta^{13}\text{C}$  of  $-10\%$  to  $-12\%$  in graphite can be achieved when the mineral siderite ( $\text{FeCO}_3$ ) is thermally decomposed at temperatures above  $450^\circ\text{C}$  (van Zuilen, Lepland & Arrhenius 2002):



The resulting magnetite ( $\text{Fe}_3\text{O}_4$ ) and isotopically light graphite (C) remain in the rock while the  $\text{CO}_2$  escapes. Van Zuilen et al. also suggest that recent organic material possibly emplaced by percolating ground water may also play a role in the especially light graphite values. Though the original claims for life reported  $\delta^{13}\text{C} \approx -28\%$  (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  $\delta^{13}\text{C}$  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 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 any 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  $\sim 10^8$  years or less, whereas if life did not originate until 3.45 Gya or 3.1 Gya, that timescale was  $\sim 10^9$  years. Some large asteroids and perhaps comets in the early solar system probably sustained liquid water interiors

<sup>14</sup>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.





(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  $\tau_1$  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  $\tau_1$  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  $\tau_1$  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

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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, unsupported, 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 &



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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.

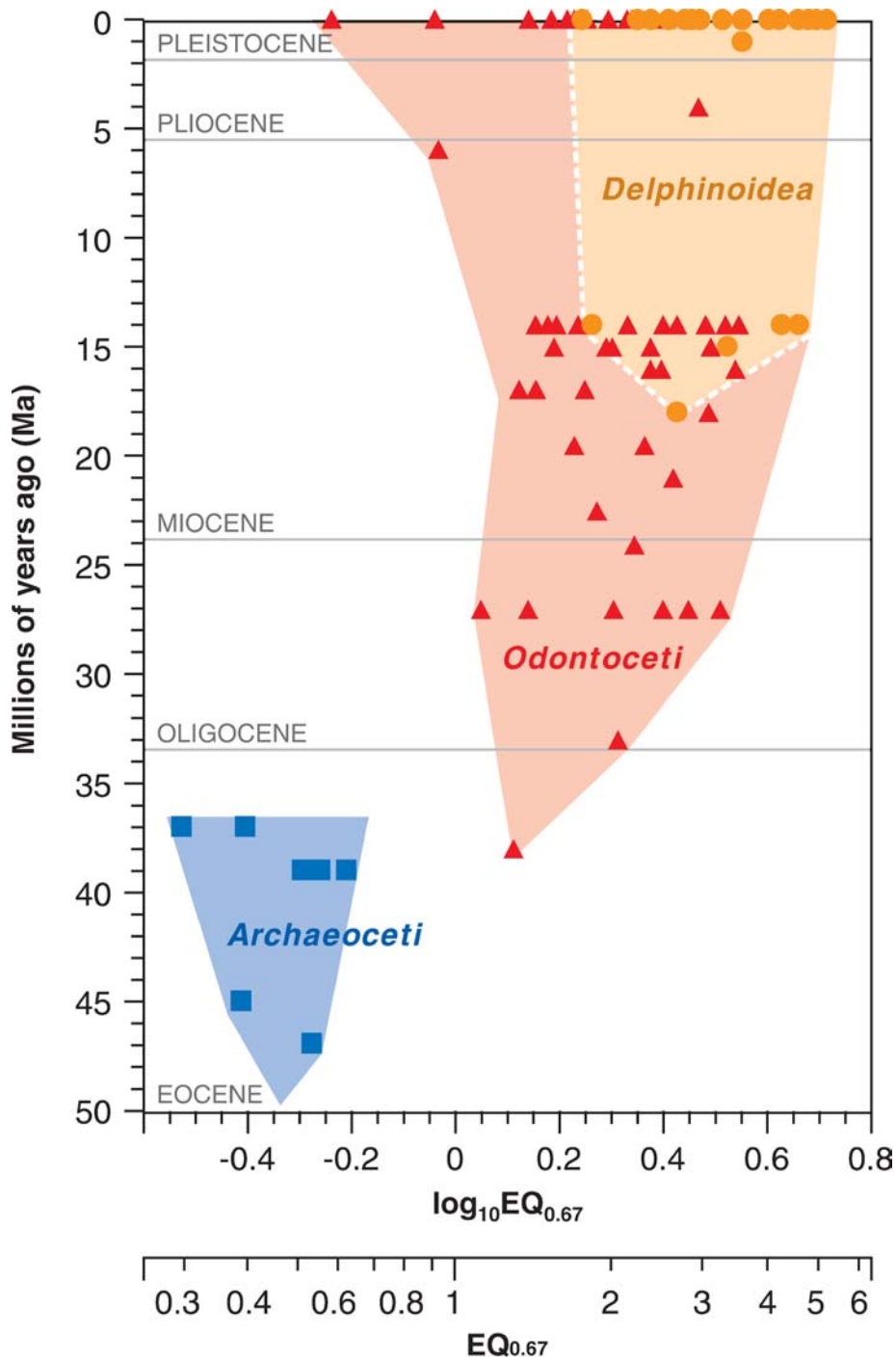
## 11. EVOLUTION OF INTELLIGENCE

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 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.,  $EQ_{0.67} = (\text{brain weight}) / [0.12 (\text{body weight})^{0.67}]$ , 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 innovative 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 whale species, one can further begin to test quantitatively familiar assertions, such as the conventional

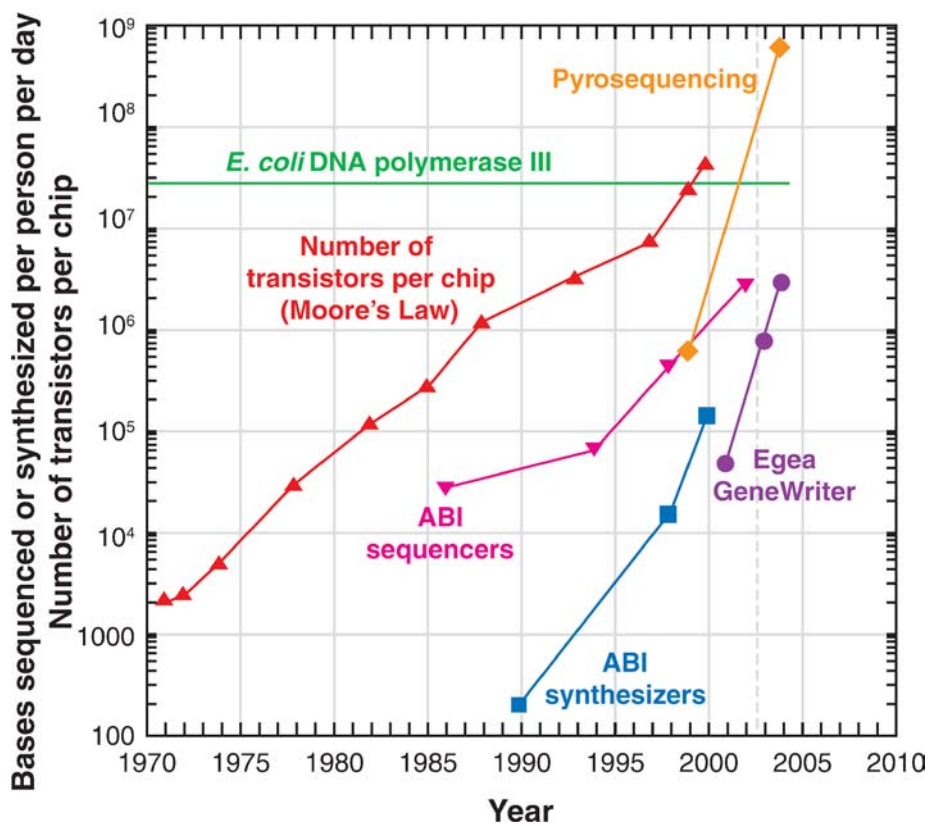




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is that the timescale for the one or the other of these to be realized is much shorter than the timescale for the realization of interstellar spaceflight (Hart 1985, Vinge 1993). We should not exaggerate the ease or casualness with which substantial 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 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).







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