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Research Paper

Assessing the Plausibility of Life on Other Worlds

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ABSTRACT

As the field of astrobiology matures and search strategies for life on other worlds are developed, the need to analyze in a systematic way the plausibility for life on other planetary systems becomes increasingly apparent. We propose the adoption of a simple plausibility of life (POL) rating system based on specific criteria. Category I applies to any body shown to have conditions essentially equivalent to those on Earth. Category II applies to bodies for which there is evidence of liquid water and sources of energy and where organic compounds have been detected or can reasonably be inferred (Mars, Europa). Category III applies to worlds where conditions are physically extreme but possibly capable of supporting exotic forms of life unknown on Earth (Titan, Triton). Category IV applies to bodies that could have seen the origin of life prior to the development of conditions so harsh as to make its perseverance at present unlikely but conceivable in isolated habitats (Venus, Io). Category V would be reserved for sites where conditions are so unfavorable for life by any reasonable definition that its origin or persistence there cannot be rated a realistic probability (the Sun, gas giant planets). The proposed system is intended to be generic. It assumes that life is based on polymeric chemistry occurring in a liquid medium with uptake and degradation of energy from the environment. Without any additional specific assumptions about the nature of life, the POL system is universally applicable. Key Words: Plausibility of life—Requirements for life—Origin of life—Persistence of life—Solar system. Astrobiology 1, 143–160.

INTRODUCTION

ROBOTIC EXPLORATION of the outer solar system has revolutionized our view of planetary systems beyond Mars. To the seminal observations of the Pioneer and Voyager missions, which revealed a more diverse and heterogeneous collection of planets and satellites than previously imagined, will be added a wealth of new data from the Galileo spacecraft currently orbiting Jupiter and the Cassini/Huygens flight now en route to Saturn. The need for a systematic assessment of the plausibility for life on a growing multitude of candidate planetary bodies is based upon our continued exploration of planetary bodies in our solar system and the detection almost weekly of planetary systems around other suns. To meet this need, we propose a Plausibility of Life (POL) rating system for estimating the chance that life could exist on another planetary body. The POL rating is based on the application of contemporary knowledge to a set of objective criteria associated with the plausibility that life could have originated and persisted. Its purpose is to provide a context for ongoing evaluations of mission priorities and a structure for debating

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the potential for life under specified circumstances.

Our solar system consists of bodies that span the full range of plausibilities covered by the system, from the certainty of life on Earth (POL of I) to the near-certainty of its absence in the Sun (POL of V). To illustrate the application of the system, we have assigned a POL value to each of the planets and major satellites in the solar system.

CRITERIA AND ASSUMPTIONS

The proposed categorical system is based on criteria derived from a minimal definition of life. The necessary and, in our view, sufficient criteria for the appearance of life are the presence of (1) a fluid medium, (2) source of energy, and (3) constituents and conditions compatible with polymeric chemistry. Key assumptions are that (1) life arises quickly under appropriate formative conditions and (2) remains static in stable environments or adapts to changing environments.

REQUIREMENTS FOR LIFE

Specifying a set of minimal requirements for life requires a clear definition of life. While this has been an ongoing and unresolved debate for decades, most formal attempts to define life include reference to its complexity (high information content) and low entropy state of disequilibrium with the environment (Schroedinger, 1944; Monod, 1971; Margulis and Sagan, 1995; Lahav, 1999; Schulze-Makuch et al., 2000). Complexity is presumed to be based at the chemical level on polymeric molecules joined by covalent bonds (Lwoff, 1962). Carbon appears to be the only element capable of forming polymers that readily undergo chemical alterations under the physical conditions prevailing on Earth, and organic molecules are now known to be pervasive throughout the observable universe. Life, then, is often assumed to be carbon-based. However, other polymer-forming elements are conceivable under exotic physicochemical conditions (Sagan, 1994). Definitions of life need not be tied to a carbon base alone. Whatever the molecular backbone of its complex chemistry, life requires a flow of energy to organize its material substance and maintain its low entropic state (Morowitz, 1968).

Building and maintaining complex chemical structures are endergonic processes. Therefore, an external energy source is universally accepted as another minimal requirement for life. Light and oxidation of inorganic compounds fuel the biosphere on Earth, so wherever light and a means for sustaining oxidation–reduction cycles can be demonstrated, the possibility for maintaining life is present. However, other forms of energy, from thermal gradients to kinetic motion to magnetic fields, can be found on worlds devoid of both light and oxygen and could serve as energy sources for life (Schulze-Makuch and Irwin, 2001).

Finally, a fluid medium is presumed necessary for constraining without confining the movement of the constituents of living entities and sustaining the rates of chemical reaction necessary to support living processes. This assumption is usually taken to mean a liquid medium and most often presumed to be water, though organic compounds and water mixtures with ammonia and other miscible molecules can exist in liquid form at temperatures well below the freezing point of water. That a fluid medium is necessary for harboring life is the most speculative of the proposed criteria, as the possibility that life could exist in dense atmospheres has also been suggested (Sagan and Salpeter, 1976). There is, for example, experimental and observational evidence for organic synthesis in Jupiter's atmosphere (Sagan et al., 1967; Raulin and Bossard, 1985; Guillemin, 2000). However, it is difficult to envision how the boundary conditions necessary for compartmentalizing the flow of energy and restricting the population of interacting molecules could be established under such conditions. Thus, while the possibility cannot be excluded that life could form and persist in dense gaseous environments, the plausibility must be rated as extremely low.

In considering the plausibility of extant life, the *origin* of life and its *persistence* need to be evaluated separately, since the conditions under which life might have arisen are not necessarily—and perhaps seldom are—those that exist at present. Thus, our assumptions relating to the origin and persistence of life are considered separately as follows.

ASSUMPTIONS ABOUT THE ORIGIN OF LIFE

The widely accepted accretion model of solar system formation proposes that planetary bodies form in situ around concentrated masses (suns) at the center of their orbits (Cassen and Woolum, 1999). The accretion process involves cataclysmic energy release through a period of bombardment that sustains high temperatures until the accretion process subsides to a negligible level. Since water is a common compound throughout the universe, it may have accumulated for a period of time on the surfaces of planetary bodies. Planets massive enough to form metallic cores containing heavy elements may continue to be heated internally by radioactive decay, even if the surface turns to ice once the body has cooled. Alternatively, those susceptible to tidal gravitational forces may be heated by friction (Buratti, 1999). In either case, the retention of water in liquid form at some depth beneath the surface can reasonably be assumed.

On Earth several lines of evidence—particularly from microbial fossils (Schopf, 1983, 1999) and carbon radioisotope data (Mojzsis et al., 1996; Rosing, 1999; Mojzsis and Harrison, 2000)—collectively point to a very early date for the appearance of life on Earth. Evidence of biogenic carbon fractionation is preserved in the oldest surviving sedimentary rock, a 3.85-billion-year-old banded iron formation on Akilia Island (Nutman et al., 1997). Data obtained from Mojzsis and Arrhenius (1998) indicate diverse phosphate-utilizing phototrophs and methanotrophs could have been present on Earth prior to 3.85 Ga. The window for the emergence of life beyond the time when the surface would have been recurrently sterilized by ongoing bombardment (3.9–3.8 Ga) has been estimated to range from 200 million years (Cairns-Smith, 1982) to 10 million years (Miller and Lazcano, 1996), pointing to the very early emergence of life.

The emergence of self-organizing systems is regarded as inevitable under appropriate conditions by a number of complexity theorists (Gel-Mann, 1994; Goodwin, 1994; Kauffman, 1995). Assuming the presence of the necessary organic building blocks, whether formed on Earth or delivered by meteorites from points of extraterrestrial origin (Miller and Orgel, 1974; Cairns-Smith, 1982; McKay and Davis, 1999), the emergence of life relatively quickly under favorable conditions is not regarded as improbable.

Davis and McKay (1996) have suggested that the plausibility of finding life on other worlds should be evaluated in light of current theories about the origin of life. This strategy works well for worlds on which conditions similar to those of early Earth are known or can be assumed to have existed, since theories of the origin of life have been formulated largely with early Earth conditions in mind. On worlds where conditions may always have been radically different from those of early Earth and exotic forms of life could have originated, the utility of using current theories regarding the origin of life are limited. Given this limitation, we follow the lead of Davis and McKay (1996) and consider the plausibility that life could have originated on a planetary body only if a reasonable theory for its origin can be envisioned. We then consider the plausibility that life could have persisted as a separate but necessary requirement for the current existence of life.

ASSUMPTIONS ABOUT THE PERSISTENCE OF LIFE

Under constant environmental conditions, mutations that lead to deviations from optimally adapted characteristics are selected against and tend not to survive. Under such conditions, natural selection *stabilizes* the metabolic, morphological, and physiological attributes of organisms, and they remain static. When the environment changes, biological characteristics that formerly were favorable may become unfavorable, and vice versa. Under these conditions, natural selection favors adaptations that fit the organism better for its new environment. An organism's characteristics thus shift in the direction favored by the changed environment. This type of *directional* selection has been observed to occur rapidly in nature under altered environmental conditions and has been induced very rapidly under laboratory conditions (Fitch and Ayala, 1994; Post et al., 1999; Riley et al., 2001).

Microbial life is pervasive at the Earth's surface where liquid water, oxygen, and sunlight provide propitious conditions for aerobic photoautotrophs and heterotrophs. In those environments where conditions have remained stable, the microbial descendents of ancestral forms have remained relatively unchanged by the restraint of stabilizing selection. But, life is also abundant beneath the Earth's surface in the absence of readily available oxygen and sunlight. For example, chemoautotrophs thrive in deep basalt aquifers by oxidizing hydrogen released from the abiotic reaction of basalt with water (Stevens and McKinley, 1995). Chemoautotrophs exist in near anoxic environments under tremendous pressures in regions of steep thermal gradients at deep ocean vents (Delaney et al., 2001). Additional examples of survival mechanisms for life in extreme conditions will be forthcoming as we come to know the full range of microbial biodiversity. Thus, in those environments that changed considerably from the conditions under which life originated, the descendents adapted under the impetus of directional selection to a great variety of conditions, including those inimical to multicellular life based on photosynthesis.

Given that stabilizing selection and directional selection have facilitated the persistence of life in spite of the atmospheric, lithospheric, and hydrospheric changes that have occurred on Earth since life originated, it can reasonably be assumed that such processes would occur on other planets.

POL CATEGORIES: DEFINITIONS

We propose a five-scale rating to cover the range of plausibilities for life on other worlds. Life is most likely to exist where the minimal conditions of liquid water, organic chemistry, and a source of energy are found. This condition is assigned to category I.

If those conditions ever existed on another planet and could still exist at some site on, above, or beneath its surface, life could have survived and persisted through stabilizing selection. This circumstance is assigned to category II. Although it is assumed for this category that the liquid be water and the complex chemistry be carbon-based, we do not make assumptions about the nature of the energy sources, so that worlds where light is not available are not precluded from this category.

If some form of liquid exists on another planet in the presence of complex chemicals and a source of energy, a form of life that differs from that on Earth could be found. This situation, assigned to category III, does not assume that the liquid is water (though water mixed with organic compounds is most likely) or that the polymeric chemistry is necessarily carbon-based (though credible models of alternatives have not been advanced). Worlds where some form of liquid at an extreme combination of temperature and pressure can exist fit into this category.

Reserved for category IV are those worlds where conditions for the origin of life could have existed at one time but can no longer do so. The conditions on such worlds are so extreme that the stability of complex molecules and/or the availability of liquid is doubtful, but the possibility that pockets of opportunity for the persistence of life could still exist, most likely in the interior, cannot be precluded.

Finally, in those sites in the universe where the present physicochemical challenges are so great that life, by any reasonable definition, could not exist are assigned to category V. The formal definition of each category is given in Table 1, along with examples.

POL CATEGORIES: EXAMPLES

Our solar system consists of bodies that span the full range of plausibilities covered by the POL system, from the certainty of life on Earth (POL of I) to the near-certainty of its absence in the Sun (POL of V). To illustrate the application of the system, we have assigned a POL value to each of the planets and major satellites in our solar system (Tables 2 and 3). In the following sections, we document the argument for these assignments with prominent examples for each of the five categories. In arriving at the POL rating, consideration is given first to the plausibility that life could have originated under circumstances presumed to have existed in the past, then to the plausibility that life could have persisted as the planetary bodies evolved to their present state.

POL: High (POL of I)

A POL of I is reserved for those bodies on which conditions are substantially similar to Earth. Consistent with the fact that Earth is the only known site of life at the present time, it stands alone in this category. While the occurrence of Earth-like planets may be rare (Ward and Brownlee, 2000), it is inconceivable that they do not exist somewhere. By inference, the probability of life on Earth-like planets elsewhere is high.

POL: Favorable (POL of II)

A POL of II is used for circumstances in which there is evidence for the past or present existence of liquid water, availability of energy sources, and where the existence of organic compounds can be inferred. Since organic molecules appear to be pervasive throughout the universe, the last criterion is equivalent to identifying conditions under which they can be reasonably expected to

TABLE 1. POL RATINGS

Rating	Definition	Examples
I	Demonstrable presence of liquid water, readily available energy, and organic compounds	Earth
II	Evidence for the past or present existence of liquid water, availability of energy, and inference of organic compounds	Mars, Europa, Ganymede
III	Physically extreme conditions, but with evidence of energy sources and complex chemistry possibly suitable for life forms unknown on Earth	Titan, Triton, Enceladus
IV	Reasonable inference of past conditions suitable for the origin of life prior to the development of conditions so harsh as to make its perseverance at present unlikely but conceivable in isolated habitats	Mercury, Venus, Io
V	Conditions so unfavorable for life by any reasonable definition that its origin or persistence cannot be rated a realistic probability	Sun, Moon, gas giant planets

be stable. At least two sites—Mars and Europa—qualify for this category.

1. Mars. The most compelling factor favoring the possibility of life on Mars is the abundance of liquid water on its surface early in its history and the possibility of water eruptions to its surface at the present time (Carr, 1996; Bridges and Grady, 1999; Malin and Edgett, 2000).

Topographic evidence for the flow and pooling of water on the surface of Mars is beyond dispute (Carr, 1986), though at least two mechanisms have been proposed (Carr, 1999). In the older surface regions, the physical character of the channels is most consistent with large flooding events, apparently originating from subsurface eruptions. Other channels show evidence of runoff, possibly from precipitation, with tributaries turning into single wider channels. The nature of crater ejecta has also been interpreted as consistent with the extrusion of mud upon impact (Carr, 1999).

At the present time, enough water–ice is present at the poles to cover the Martian surface with a uniform layer of liquid 10–30 m deep (Fanale, 1999). Even so, this amount of water falls short of what appears to have been needed to account for the topographic features. Therefore, the presence of substantial groundwater reservoirs is assumed (Carr, 1999). Semiglobal groundwater flow systems appear to be likely, with recharge areas located at the poles and discharge areas located in the desert lowlands near the equator (Risner, 1989). Groundwater flow would largely be confined between the basement bedrock and the overlying permafrost layer, occasionally percolating to the surface where fractures in the permafrost layer would provide a suitable conduit after a certain pressure threshold is overcome. Physical evidence for past, sometimes massive, eruptions from the subsurface, especially in the older highland regions, is abundant (McKay and Davis, 1999). Images recently processed from the Global Surveyor suggest geologically recent, or possibly even contemporary, eruptions from the sides of craters at a consistent depth beneath the presumed permafrost zone (Malin and Edgett, 2000).

While the availability of liquid water at some point in the past is not disputed, a thermal and atmospheric history for Mars that would compel the existence of liquid water is not as clear (Fanale, 1999). Nevertheless, if liquid water flowed on the surface, temperatures compatible with the origin and perseverance of life must be assumed. Such temperatures exist transiently on the surface even now. All theories for the origin of life appear to be compatible with conditions on Mars during its early history (Davis and McKay, 1996). Therefore, the origin of life on Mars is clearly plausible.

The persistence of life on the surface of Mars today seems highly unlikely, however, given the extremely desiccating conditions, thin atmosphere with high UV radiation, and lack of magnetospheric shielding. But as water became increasingly internalized on Mars, so could its biota (McKay and Davis, 1999). Life could have retreated to the deep subsurface and continued to thrive as microbes do on Earth in deep granitic and basalt aquifers (Olson et al., 1981; Pedersen

Table 2. Basis for Assignment of POL Rating System to Major Planetary Bodies in the Solar System

Body	*POL*	*Water*	*Chemistry*	*Energy*	*Plausibility for life*
Mercury	IV	Possible water–ice at poles		Solar radiation (light and heat); geothermal (radioactive decay)	Low—intense solar radiation; little if any geological cycling
Venus	IV	No evidence	Extensive resurfacing → geological activity and chemical recycling	Solar; geothermal (radioactive decay); pressure	Low—extreme heat at surface; highly caustic atmosphere; no evidence of water
Moon	V	No evidence, except for minute amount at poles		Solar radiation (light)	Remote—extremely dry, no protective atmosphere
Mars	II	Surface erosion by flowing water	Oxidized surface	Solar radiation (light and heat); geothermal past or present	Favorable—liquid water on surface in the past; possible subsurface liquid water now; some surface warming
Jupiter Saturn Uranus Neptune	V V V V	Gas giants with indistinct high-pressure atmosphere/liquid transitions	Organic and nitrogen compounds	Pressure; convection; magnetism	Remote—abundant energy but lack of solid substrates or sharp physical transitions; temperature and pressure extremes
Pluto, Charon	V	Density $\sim$2.1 → rock/ice mixture	Mix of light and dark features → complex chemistry	Chemical	Remote—extreme cold; lack of evidence for any liquid

Table 3. Basis for Assignment of POL Rating System to Major Satellites in the Solar System

Body	*POL*	*Water*	*Chemistry*	*Energy*	*Plausibility for Life*
Moons of Jupiter					
Io	IV	Volcanic activity generates thin atmosphere	Surface coloration → complex chemistry	Geothermal (tidal flexing, radioactive decay); chemical; magnetic	Low—sharp thermal gradients and geochemical cycling; but harsh temperature and radiation
Europa Ganymede	II II	Water ice surface, magnetic field and resurfacing → liquid water	Surface coloration → complex chemistry and chemical recycling	Geothermal (tidal flexing, radioactive decay); Jovian radiation	Favorable—numerous energy sources; likely subsurface water; geochemical cycling
Callisto	III	Low density → mostly water–ice		Geothermal (limited tidal flexing, radioactive decay); Jovian radiation	Moderate—possible subsurface liquid water, but little energy flux
Moons of Saturn					
Tethys Dione Rhea	IV IV IV	Very low density and high albedo mostly water–ice		Magnetic; strong Saturnian radiation	Low—little evidence for liquid water at present
Enceladus	III	Extensive resurfacing, with evidence of ice geysers		Geothermal (tidal flexing); magnetic; convectional	Moderate—possible subsurface liquid water with several energy sources
Iapetus	IV	Low density and moderate albedo → mostly ice	Dark leading edge → hydrocarbon chemistry	Chemical	Low—no evidence for liquid water at present
Titan	III	Density $\simeq$ 1.8 → organic liquids and/or water–ice, with solid core	Dense, colored atmosphere → complex chemistry	Chemical; geothermal (radioactive decay)	Moderate—complex organic chemistry and reducing atmosphere

(*continued next page*)

TABLE 3. BASIS FOR ASSIGNMENT OF POL RATING SYSTEM TO MAJOR SATELLITES IN THE SOLAR SYSTEM (CONT'D)

Body	*POL*	*Water*	*Chemistry*	*Energy*	*Plausibility for Life*
Moons of Uranus					
Titania	III	Evidence of liquid flow in canyons		Geothermal	Moderate—Possible subsurface or recent surface liquid
Ariel	IV	High albedo and density $\simeq$ 1.5–1.7 $\rightarrow$ rock/ice		Geothermal?	Low—small size and insufficient evidence for energy gradients
Miranda	IV				
Umbriel	IV				
Oberon	IV				
Moon of Neptune					
Triton	III	Density $\simeq$ 2 $\rightarrow$ rocky core with water/ice surface	Surface coloration $\rightarrow$ complex chemistry, unusual surface features $\rightarrow$ internal energy	Chemical; elliptical orbit $\rightarrow$ tidal flexing and seasonal temperatures	Moderate—complex chemistry and several energy sources, with possible subsurface liquid
Comets and asteroids	V	Rock/ice mixture	Abundant water–ice; possible hydrothermal alteration in parent bodies	Chemical	Remote—extreme cold, no atmosphere, no persistent internal energy source

and Ekendahl, 1990; Stevens and McKinley, 1995). While the plate tectonic activity of earliest Martian history has ceased, volcanism most likely has continued to the present time (Connerney et al., 1999; Sleep, 1994). Subsurface geothermal areas may thus provide a suitable habitat for chemoautotrophic organisms that are sustained by oxidizing free hydrogen to water in the presence of carbon dioxide provided by volcanic outgassing or by the atmosphere. Alternatively, chemoautotrophs could reduce carbon dioxide to methane or recycle atmospheric carbon dioxide and oxygen, which are codeposited on the polar ice caps. Basal melting of polar deposits consisting of carbon dioxide and other constituents (Risner, 1989), including oxygen that may be codeposited in the ice caps, would allow water to carry these constituents in dissolved form toward the deeper zones of the groundwater flow system, where thermodynamically favorable oxidation reactions could sustain a limited but relatively stable subsurface microbial ecosystem.

Solar energy sources have been available continuously on Mars and could still sustain life in the fringe areas of the polar caps. Analogies for this type of life style are found on Earth in the Antarctic dry valleys, where phototrophs living in the interior of rocks are shielded from the hostile environment (Friedmann, 1982). Though the daytime surface on Mars is warm enough at midlatitudes to support physiological processes as we know them, the presence of lethal radiation would limit life to the subsurface. However, beneath the surface the temperature drops precipitously to <220°K within a few centimeters (Carr, 1999). Thus, life would appear to be limited to regions of groundwater below the permafrost line, where the sources of energy are less certain. Given that Earth-like conditions existed on Mars during its early history, that liquid water may still be present below the surface, and that energy is readily available, Mars rates a POL of II.

2. *Europa.* Jupiter's smallest major satellite is the smoothest body in the solar system. Though covered with a water–ice shell estimated to be 100–200 km thick (Anderson et al., 1997; Carr et al., 1998), Europa is second only to Io in having such a high density (2.99 g cm^{-3}) among the satellites of the outer planets. This, in combination with gravitational measurements, is consistent with a solid core of mixed metals and silicates or a metallic center with a silicate shell beneath the water–ice shell (Anderson et al., 1997).

The possibility of life on Europa has increased with the discovery of new evidence that indicates a salt-bearing liquid ocean lies beneath the frozen ice crust. The presence of a subsurface liquid water layer is consistent with models for the origin of the larger outer satellites (Consolmagno and Lewis, 1976). Current evidence in support of a subsurface liquid ocean includes (1) the asynchronous rotation of Europa, which implies a friction-generating subsurface material (Geissler et al., 1998), (2) surface fracture features consistent with mobile icebergs driven by subsurface liquid (Carr et al., 1998; Hoppa et al., 1999), and (3) magnetic fields induced by eddy currents in a mobile conducting medium within the body of the satellite (Khurana et al., 1998).

If water was ever liquid at the surface on Europa, all current theories about the origin of life on Earth could potentially apply to Europa. If an ice sheet covered the moon entirely at an early point in its history, an extraterrestrial origin for life would have been precluded. However, all of the models for a terrestrial origin of life could apply. Therefore, the origin of life on Europa is quite plausible.

Life could have persisted on Europa if water is indeed liquid beneath its icy crust. By analogy with deep ocean hydrothermal systems that support rich ecosystems on Earth, even dark and anoxic environments at the bottom of Europan oceans could provide energy to drive living processes. Experimental support for a methanogenesis-driven biosphere on Europa that does not require a supply of oxidants has been obtained by Navarro-Gonzalez et al. (2001). Energetic particles from the Jovian magnetosphere deliver energy to the surface of Europa (Sieger et al., 1998) and possibly generate low amounts of oxygen in the atmosphere that could contribute to oxidation–reduction chemical cycles (Chyba, 2000). Europa's high density and measurements of an electromagnetic field (240 nanoteslas) at its surface (Kivelson et al., 1997) suggest the possibility of a metallic molten core that could generate internal thermal energy. Thermal energy and kinetic energy derived from convection currents (Schulze-Makuch and Irwin, 2001) have also been suggested as the basis for bioenergetics on Europa. The evidence of extensive resurfacing clearly indicates the dissipation of a large amount of energy. Whether energy in these forms could be harvested by living systems exposed to them over their evolutionary history is an open question, but the availability of energy is not in doubt.

Differential coloration associated in particular with fracture zones on the surface indicates chemical cycling of sulfur compounds (Carlson et al., 1999) and salts associated with the surfacing and evaporation of salt-bearing liquid. The presence of small amounts of oxygen (Hall et al., 1995; Sieger et al., 1998) for oxidation reactions in Europa's atmosphere could also account for some of the coloration.

Whether Europa is a possible habitat for the origin and persistence of life is not known. Until an energy source other than tidal friction can be shown convincingly and modeled persuasively as a plausible energy source for living systems, or at least until some manifestation of tidal energy has been modeled as a credible source of biogenetic energy, enthusiasm for the search for life on Europa should be tempered. Given the apparent existence of liquid water on Europa and its possible existence over the entire extent of Europan history, as well as the availability of several possible energy sources, this satellite also rates a POL of II, giving it a plausibility rating equal to that of Mars as a possible outpost for life elsewhere in the solar system.

POL: Moderate (POL of III)

A POL of III applies to bodies where conditions are extreme compared with those of Earth but where the minimal criteria of energy, liquid, and complex chemistry in some form are satisfied. This category includes sites too distant from the sun for effective photosynthesis but where other sources of energy are known to be present and excessive cold or heat preclude liquid water but not water–organic mixtures or pure organic liquids. While complex molecules based on polymers of atoms other than carbon are difficult to envision, their existence in extreme environments cannot be precluded (Sagan, 1994). Saturn's moon Titan and Neptune's moon Triton fit comfortably into this POL category of III.

1. Titan. Titan is the only other body known to have a nitrogen-rich atmosphere like that of Earth. The other major gases are methane (0.5–4%), argon (0–6%), traces of CO_2, and many organic compounds, but little or no oxygen. The surface is obscured from visual light penetration by a permanent haze of photochemically induced reaction products in the nitrogen–methane atmosphere (Coustenis and Lorenz, 1999). Organic liquids are predicted to precipitate at a slow rate (Lorenz, 1993) and then fall through a clear troposphere of $\sim$40 km onto an $\sim$90°K surface. Titan's density is consistent with the presence of a rocky-metallic core of sufficient mass to provide radiogenic heating. These features and the possibility of a magnetosphere (Kivelson and Bagenal, 1999) are consistent with a potential energy source on Titan.

The presence of abundant organic compounds, possibly sufficient to coat the entire surface (Spiker, 1997), provides the strongest stimulant to speculations about the possibility of life on Titan. The possibility that complex organic chemistry could exist in liquid mixtures fuels this speculation. In the absence of water, methane or ethane, which could be present on or near the surface, could act as an organic solvent (Vaas, 1990), though the ability of ethane to dissolve abiotically produced organic molecules has been questioned (McKay, 1996). If Titan is $\geq$80°K warmer in its interior, pockets of liquid water–ammonia would be stable since the peritectic melting point of this mixture is $\sim$176°K (Coustenis and Lorenz, 1999). Some models of Titan's interior include underground reservoirs of water–ammonia–organic compound mixtures (Spiker, 1997).

The geophysical and atmospheric evolution of Titan is not known, so speculating on conditions amenable to the origin of life there are difficult. To the extent that organic compounds have long been abundant and liquid has been present, minimal conditions for the origin of life forms other than phototrophs have existed on Titan.

Low temperature appears to be the greatest obstacle to the perseverance of life on Titan. In addition, the early liquid environment on Titan would likely have been sufficiently different from that of any of the other rocky planets. If life formed, it would have been exotic by Earth standards. If life persists today, it is likely to be even more exotic. Whether exotic life forms could have persisted on Titan would depend upon whether a liquid medium and an energy source (e.g., radiogenic heating or reduced organic compounds coupled to an oxidation mechanism) were available. The arrival of the Huygen's probe in January 2005, will provide new light into these prospects. Until additional information about Titan is acquired, the possibility that an exotic form of life could be found on Titan justifies assigning it a POL of III.

2. Triton. Triton is the seventh largest planetary satellite and Neptune's only major moon. Though the coldest body yet found in the solar system (38°K at the surface), we rate it as a possible reservoir for life because of its unusual history and current condition.

In view of numerous geophysical similarities to Pluto and Charon, Tritan is thought to be a captured planetesimal that accreted in solar orbit (McKinnon and Kirk, 1999). Since Neptune, alone among the gas giant planets, lacks any sizeable satellites other than Triton and since the capture of a body that large would have been very difficult without major collisions to slow its momentum, current models postulate that cataclysmic collisions with a preexisting satellite system slowed Triton's trajectory into a highly elliptical orbit that progressively regularized to its present circular but oblique and tidally locked orbit around Neptune (McKinnon and Kirk, 1999).

The preferred model for Triton's capture by Neptune suggests that tidal friction at one time would have been sufficient to melt the satellite recurrently throughout its early history. Current models favor a differentiated interior, with a metal inner core, silicate outer core, and ice mantle (McKinnon and Kirk, 1999). Therefore, prospects for the existence of liquid water at one or more points in Triton's history are reasonable.

The possibility that life originated and persisted on Triton is based upon the following considerations: (1) If Triton indeed originated in solar orbit, it should have accreted a substantial carbonaceous component. The occurrence of dark spots (maculae) and coloration changes over brief periods likewise indicates the presence of complex chemistry. (2) Evidence of past and present energy sources is abundant. Relatively recent resurfacing and other volcanic features indicate a high level of geological activity. Plumes consistent with geyser-like activity have been observed. The atmosphere is thin but dynamic. The unique cantaloupe terrain resembles Earth-like diapiric features, indicative of internal heat-generated or compositional buoyancy. (3) Triton's highly inclined orbit generates significant seasonal fluxes over Neptune's 165-year orbital cycle, and the fluxes are further complicated by precession of Triton's orbital plane relative to Neptune. These irregular cycles mean that environmental change is a constant on Triton. (4) Triton's density of >2 g cm^{-3} and its point of origin in the outer solar system away from a giant planet are consistent with a differentiated interior containing an intermediate silicate layer providing solid surfaces beneath a thick insulating layer of mainly water–ice.

The case for life on Triton is hampered by the lack of knowledge about when and for how long liquid water was available. It would be weakened further if subsequent data indicate a differentiated interior is unlikely, the prospects of continued internal heating is low, or the surface coloration changes are explicable by means other than complex chemistry. While conditions on Triton appear to be extreme at present, they were quite possibly amenable to the origin of chemotrophic life at an earlier point in its history, which could still be present if a liquid environment persists below the surface. Based on the limited information available, we assign Triton a POL of III. The data required for assessing the plausibility for life more precisely could be obtained by robotic missions that are technologically feasible at the present time.

POL: low (POL of IV)

A POL of IV applies to worlds on which past conditions suitable for the origin of life can reasonably be inferred, prior to the development of conditions so harsh as to make the perseverance of life at present unlikely but conceivable in isolated habitats. Jupiter's moon, Io, and the planet Venus fall into this category.

1. Io. Io joins Titan as one of the solar system's most exotic possible outposts for life. At the present time it is the most volcanically active body known in the universe. Half a dozen or more volcanoes can be seen, and many more "stealth" geysers are probably erupting at any given time (Matson and Blaney, 1999). Tidal friction arising from Io's eccentric orbit induced by resonance with Europa is the primary source of the tremendous thermal emissions, though recent magnetospheric evidence is consistent with the presence of a molten metallic core as well (Kivelson et al., 1996). Io has an extremely thin atmosphere of patchy SO_2 and SO (Lellouch, 1996) devoid of detectable water vapor. The surface consists of frozen SO_2 and a variety of sulfurous compounds, with a mixture of silicate minerals. It has an extremely energetic plasma particle interaction with Jupiter (Geissler et al., 1999).

Magnesium-rich silicate lava at temperatures approaching 2,000°K flows onto a frozen surface as low as 160°K (McEwen et al., 1998; Spencer et al., 2000). Hot spots in the 500–600°K range are common, and the median temperature of the Loki Patera caldera floor is 273°K (Lopes-Gautier et al., 2000). This complex thermal profile has recently been shown to be quite dynamic, with documentation of movement of lava across frozen fields of SO_2 at ~5 m/day (Kieffer et al., 2000). A model of this behavior envisions lava flowing across a snowfield of SO_2 and developing ". . . a layered stratigraphy, consisting of hot, possibly supercritical fluid, as well as various mixtures of vapor, liquid, and solid phases . . . producing a complex fluid . . . 'boundary-layer slurry' "(Kieffer et al., 2000).

Io meets none of the conventional standards of what constitutes a benign habitat for life and in most respects would appear to be hostile to any living system. However, models of Io's origin suggest that it formed at an average temperature of 250°K in a region of the solar system where water–ice is plentiful (Consolmagno and Lewis, 1976). The combination of liquid water and geothermal heat could at one time have made the origin of life as plausible on Io as it is on the neighboring satellite of Europa. As water was lost from the surface, life could have retreated to underground stores, perhaps adapting to extreme liquid environments such as the complex fluid mixtures envisioned by Kieffer et al. (2000). Abundantly available geothermal activity, and possibly reduced sulfur compounds, could have provided energy sources. While most of the time such organisms might have persisted in a frozen spore-like state of inactivity, moving thermal boundaries from flowing lava or erupting geysers could periodically rejuvenate them.

The most serious drawback to the feasibility of life on Io is the apparent near-total absence of water today. Lacking certain knowledge that water ever existed on Io significantly reduces the possibility that life might have arisen there. But if it did, the uniquely complex thermal patterns, rich energy sources, and chemical heterogeneity of Io justify assigning it a POL of IV, indicating a small but finite plausibility for the existence of life at some point on Io.

2. Venus. Venus is very similar in size and density to Earth. This, in combination with the formation of Venus in the same general region of the solar system, has led most observers to assume that liquid water may have been present early in its history. Given the availability of abundant solar energy, life could have formed in Venusian primordial waters by all of the same possible mechanisms proposed for life's origin on Earth.

Unfortunately, that history is totally obscured by planetwide resurfacing within the most recent 750 Ma. At present, there is no current plate tectonic activity on Venus, but the planet has been, perhaps episodically, very active volcanically (Hunten, 1999). This has resulted in a dense atmosphere of CO_2 and H_2SO_4 that has generated an intense greenhouse effect with temperatures of >700°K on the surface of Venus today (Head and Basilevsky, 1999). This makes life untenable at the surface. However, it could exist in subterranean habitats if any water remains there. Water vapor is available but scarce (45 ppm at an altitude of 40 km) in the Venusian atmosphere (Hunten, 1999). Whatever groundwater persists, then, would have to be quite deep. Sunlight would not be available as an energy source, though thermal gradients from surface heating and from volcanic activity would be abundant.

The extent to which Venus and Earth were ever similar is debatable (Head and Basilevsky, 1999). The possibility that they were, however, compels us to take seriously the possibility that life arose on Venus just as it did on Earth. Whether life would have persevered, however, is unlikely. Catastrophic volcanic episodes, possibly of a recurring nature, could have sterilized all life near the surface. Desiccation may have been so complete that no depth beneath the surface provided a sufficient sanctuary. Lacking an intrinsic magnetosphere (Kivelson and Bagenal, 1999), ionizing radiation may have posed lethal threats even before desiccation and rising temperatures became hostile. But we know too little about the subsurface of Venus to rule out the persistence of life underground to the present day, and we certainly cannot rule out its perseverance prior to the catastrophic resurfacing that occurred <800 million years ago. Thus, while the chances that life persists on Venus today may seem small, the overall plausibility that it ever existed there merits a POL of IV.

POL: remote (POL of V)

The final POL of V is reserved for those bodies where conditions are so unfavorable for life by any reasonable definition that its origin or persistence cannot be rated a realistic probability. The Sun itself and, somewhat more tentatively, the gas giant planets and the Earth's Moon fall into this category.

1. Gas giant planets. Jupiter, Saturn, Uranus, and Neptune appear to be rocky planets encased in a shell primarily of hydrogen, with small amounts of helium and other elements layered in a gas–liquid–plasma continuum of increasing temperature and pressure toward the interior. While pressure and thermal gradients, as well as electromagnetic fields and lightning discharges, could provide abundant energy, the occurrence of both temperature and pressure in a range at which complex polymeric molecules could be stable seems unlikely. Except at the interface between the rocky core and the plasma, where complex molecules would almost surely be unstable, no sharp boundaries are likely to exist. Absent a solid or stable substratum, complex chemical interactions seem unlikely to occur. Under these circumstances, the origin of life, either locally or by interplanetary transfer, seems implausible. While some combination of complex chemistry, temperature, and pressure may exist somewhere in one or more of the gas giant planets, which could support life once it began (Sagan et al., 1967), until a plausible model is advanced, we rate the chance of life at those sites in the solar system as remote and assign to them a POL score of V. The same reasoning at a more compelling level applies to the Sun and any other star.

2. Moon. As the Earth's closest neighbor, the Moon was the first and still remains the only planetary body on which humans have landed and collected samples. Thus, lunar probes and the Apollo program have provided a relatively good understanding of the Moon. The Moon has no atmosphere and no global magnetic field. Temperatures range between 123°K and 373°K with solar flares and cosmic rays, making the lunar surface an inhospitable place for life (Lowman, 1999). There is no evidence of any type of liquid in the Moon's crust. Furthermore, even the amount of structural water in the lunar soil is very low. Values found range between 150 ppm and 500 ppm for lunar breccia, with somewhat higher values for lunar dust (Friedman et al., 1970). However, signatures of water–ice have recently been detected on the lunar poles (Showstack, 1998). Amino acids and their precursors have also been detected in the lunar soil but can be explained by HCN implanted by solar wind. The detected alanine and aspartic acid are attributed to terrestrial biogenic contamination (Brinton and Bada, 1996). The lack of any liquid, along with the absence of an atmosphere and magnetic field, diminishes the probability that life could have originated on the Moon to practically zero. Highland rocks and basalts that formed from melting events within the mantle originated from differentiation events during ancient lunar history shortly after the Moon accreted (Jolliff et al., 2000). There is no evidence of any type of current or recent lunar geological activity. The absence of water and a protective atmosphere since the time of its origin indicates the perseverance of life on the Moon, even if it had arisen, is implausible. Thus, we assign a POL rating of V to Earth's Moon.

Ambiguous cases

Recent evidence suggests that Ganymede has a subsurface ocean similar to Europa. Ganymede also generates a magnetic field (Kivelson and Bagenal, 1999; Showman and Malhotra, 1999) and shows evidence of geological activity (Buratti, 1999). With the presence of both an energy source and liquid water, many of the arguments favoring the appearance of life on Europa would apply to Ganymede as well. Jupiter's outermost satellite, Callisto, shares many characteristics with Europa and Ganymede and may also have a subsurface liquid ocean (Khurana et al., 1998). However, it appears to be the least differentiated of the Jovian satellites with the oldest surface, raising doubts about the availability of energy. Based on these considerations, we tentatively assign a POL of II to Ganymede and III to Callisto.

Enceladus appears to be the most geologically active of the medium-sized Saturnian satellites. Eruptions interpreted as ice geysers that could be generating material for Saturn's E-ring (Spiker, 1997) indicate an energetically active body, probably owing to tidal interactions with its neighboring satellite, Dione (Buratti, 1999). Since Enceladus shows signs of resurfacing, energy fluxes could conceivably still be generating liquid water or water–ammonia slurries at some depth beneath its surface. While the origin of life would have required liquid water or water–organic mixtures at an earlier stage of the satellite's evolution and probably would have precluded photoautotrophy at that distance (>9 A.U.) from the sun, once begun, life could conceivably have persisted beneath the surface. These considerations merit a POL of III for Enceladus.

A few other icy satellites in the outer solar system merit some consideration. Among the medium-sized satellites of Uranus, heating and differentiation have occurred on Ariel, Miranda, and possibly some of the others (Buratti, 1999). Ariel, Oberon, and Titania show faulting. In general, there is more evidence for geological activity on the satellites of Uranus than on those of Saturn. Furthermore, Umbriel, Oberon, and possibly some of the others may contain the organic-rich D-type material that characterizes the outer solar system (Buratti, 1999). Though all, with the exception of Titania, are too small to retain any radiogenic heating, the resurfacing and evidence of past liquid flow on Titania, Ariel, and Miranda suggest the flux of energy from tidal interactions. On the basis of its larger size and apparent geological activity, we assign a POL of III to Titania and IV to the others.

Of the other planets in our solar system, only Mercury merits consideration for the possibility of ever having harbored life, and we do not rate that prospect as great. That Mercury should be considered is based on the possibility that it may have had liquid water at or near its surface early in its history, when the Sun was dimmer and Mercury's distance from the Sun greater. Even today, evidence from high-resolution radar imaging indicates water–ice to be present at the north pole (Slade, 1992; Harmon et al., 2001). Surface temperatures vary from 89°K on the night side to 600°K on the day side. Since Mercury rotates at 1.5 revolutions per orbital period, the steep thermal gradient at the terminator moves slowly around the planet, providing brief periods when the surface temperature would result in liquid water, if water is present. Subsurface life would thus periodically have brief access to liquid water and moderate temperatures. The major drawbacks to the likelihood of life on Mercury are a lack of geomorphological evidence for the presence of water at any time in the past, the lack of an atmosphere, and the fact that most models of Mercury's formation do not postulate its origin under cool enough temperatures to have harbored liquid water (McKay and Davis, 1999). The ability of life either to originate or to persist on Mercury is thus doubtful, and we assign it a POL rating of IV.

The possibility that comets and asteroids could act as repositories of life remains to be considered. Arguments asserting that they could at least serve as transport vehicles for life have been advanced, based on the evidence for liquid water cores during a formative period in large comets (Irvine et al., 1980; McKay, 1997). The main arguments against the survival of life on comets are their extreme cold, lack of atmosphere, and lack of differentiation. Most asteroids suffer from the same deficiencies, though few have been considered in detail. An exception is recent work by Trombka et al. (2000), which suggests that the relatively large asteroid 433 Eros does not appear to have been exposed to global differentiation and, therefore, is lacking an internal energy source to provide heat for chemical evolution. Until more examples have been analyzed, the possibility that life could originate and persist on comets and asteroids has to be assigned a POL rating of V. However, since asteroids and particularly comets may have the capability to act as transport vehicles for life, they merit a high priority for continued scientific investigation.

DISCUSSION

Assessing the chances for life on other worlds is a speculative science. As science, it requires reference to consistent standards of inference and systematic application of reasonable assumptions. As speculation, it requires appreciation for the possibility that life at other sites in the universe could either be similar to or distinctly different from life on Earth.

The categorical system proposed here attempts to balance the need for objective science with latitude for creative speculation. It is intended to provide a baseline for discussion of those facts and assumptions most relevant to assessing the chances for life throughout the universe as data become increasingly available. At the same time, the system proposed here is intended to give latitude for envisioning life either analogous to or substantially different from the only forms of life known at present. Thus, while all definitions of life require a flow of energy to maintain a complex and ordered state in disequilibrium with the environment, the nature of that energy need not be restricted to light or oxidizable compounds as on Earth. The nature of chemical interactions among complex molecules appears to require a liquid medium, though water alone is not the only liquid that can be envisioned as a solvent for complex chemistry. Finally, the macromolecular chemistry required by most definitions of life involves stable polymers subject to interchangeable modification. Carbon-based compounds are the only class of molecules known to have the requisite combination of stability and modifiability in an isothermal liquid medium under conditions of temperature and pressure prevailing on Earth. Alternatives to carbon-based polymers that would have the same properties even under exotic conditions have not yet been modeled convincingly. Until alternatives to carbon-based life are shown to be unworkable, however, the possibility should not be excluded.

The categorical system proposed here is designed to be broad and robust enough to consider the full range of conditions found in the universe, telescoped into a small number of alternatives. Assignments based upon it are understood to be related to the state of knowledge about a potential habitat for life at a given point in time. As new information is acquired and our knowledge of planetary bodies changes, so should their POL rating. In other words, the POL rating must be regarded as a dynamic value consistent with the information currently available. Its utility lies primarily in directing consideration of the possibility for the existence of life along objective and consistent lines of argumentation.

CONCLUSIONS

A categorical system for the plausibility that life exists under specific conditions on other worlds should channel the debate about the necessity and sufficiency of those conditions and guide the search for evidence of life beyond Earth. The POL rating system proposed here provides a specific set of criteria, based on minimal generic definitions of life. The system assumes that life requires energy and complex chemical interactions in a liquid medium but allows latitude for each of the requirements for life to be satisfied in a variety of forms. Numerous planetary bodies in our solar system appear to have provided suitable conditions at some point in their history for the emergence of life. The early origin of life on Earth suggests that life may have developed independently or by interplanetary transfer at multiple sites in the solar system. As planets and moons cooled after their accretionary process, surface conditions became hostile to life as we know it on all of the planets and moons of our solar system except Earth. However, once life emerged, it is reasonable to assume that it could have adapted to the more stable and benign conditions beneath the planetary body's surface. Our systematic POL analysis of the distribution of minimal conditions for the origin and persistence of life in our solar system indicates that the search for other life would appear to be most productive on Mars, Europa, and possibly Ganymede, but Triton, Titan, and Enceladus merit consideration, as do numerous other planetary bodies and satellites that have a small but finite possibility of harboring life.

ABBREVIATION

POL, plausibility of life.

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