Project 003

Project Title: Life in the Solar System

Introduction

What exactly, makes 8 Mearth, a larger-than-Earth planet in the Gliese 581 system in Libra, a ‘habitable’ planet (Bonfils et al 2007)? What features draw us closer to investigate the possibility of life on extra-Solar planets? And what does that tell us about the possible location of life within the Solar System? Planets in the habitable zone of stars similar to the Sun, need to have enough CO_2 in the atmosphere such that liquid H_2O is maintained on the surface. Too much CO_2 and a runaway greenhouse effect ensues (viz. Venus), too little and Rayleigh scattering of stellar radiation plunges the planet into a deep freeze (Lammer 2007).

Scientists have considered the prerequisite conditions, and indicators of, life, and Kasting et al (2009) present a list which is worth paraphrasing: “…Habitability factors include surface temperature, presence of liquid water on the surface, atmospheric pressure, likelihood of plate tectonics, likelihood of atmospheric retention, clouds (cirrus or cumulus), and surface type (rock, ice, sand, water, vegetated). Further factors include the time variability of its observed characteristics, including the length of day, surface morphology (continents, oceans, and ice), large-scale weather patterns, obliquity, and seasons. Evidence for life would include the presence of various biogenic trace gases, especially O_2 and its photochemical byproduct, O_3. CH_4 is also a potential bioindicator on early-Earth type exoplanets.” And Lammer et al (2009) went on to propose four types of habitable worlds: those which developed like Earth and support “…complex, multi-cellular life forms…”, those which developed like Mars or Venus and preclude the possibility of highly evolved life, those that have subsurface oceans with refractory cores, and those which have bodies of liquid above or below ice layers.

Of course, we’re assuming here, that ‘life’ is the sort of life we know about on Earth, and since it’s the only life we know of, we’re trapped with a subjective, anthropic bias which prevents us from predicting the form of alternative life formats, and also from predicting the probability of life existing elsewhere in the universe. But let’s push on and see what we can develop…

Extra-Solar considerations somewhat skew our search towards Earth-like organisms on an Earth-like planet in an Earth-like habitable zone. Closer to home, let’s assume for the moment, that if there was intelligent life within our Solar System, then we’d know about it by now, so the hunt for extra-terrestrial life near-by, is the hunt for plants or animals or ‘something’ that qualifies as ‘life’, and has so-far been undetected by our technology. Could there be fish in the oceans of Titan, microbes in Martian soil or crustaceans under the ice at the south pole of our Moon? Could an exotic type of life be toiling away in the hydrocarbon lakes of Titan, or right under our noses on Earth?

This essay is a brief overview of the science of astrobiology as it pertains to the Solar System, and will discuss what we think life is, where it might be in the Solar System, some results of efforts to find it, and future directions of inquiry.

What is Life?

This is not as easy a question as first thought, and since we’re looking in strange and unexplored environments (space!), some time should be devoted to it. An understanding of what life actually *is*, can direct the development of missions and tools, for its detection.

Aristotle pondered the meaning and definition of living existence, but it wasn’t until Schrödinger (1944) observed that life had the curious ability to work against universal entropy, building complexity and actually passing it on to subsequent generations, that we seriously considered our understanding of the living world.

Schrödinger suggested that life fed on some sort of “negative entropy”, and scientists and philosophers have long anguished over what constitutes life, but technicians with budgets and timelines need a working definition, so they can search for it in the real world. Abercrombie et al (2007), define life as a “…complex physico-chemical system…” with two distinguishing features:

use of nucleic acid to copy and keep molecular information, and use of special proteins (enzymes) to catalyse substrate molecules into useful chemical products. They suggest that the familiar characteristics of nutrition, respiration, reproduction, excretion etc all derive from these two functions. Although not everyone believes that we *must* have a definition of life (Gayon 2010), biologists and astrobiologists would include the ability to evolve through generational mutation, as a feature which distinguishes a living entity from a duplicating crystal or computer virus (Dawkins, 2009). NASA's definition even excludes biological viruses because it *requires* life to be autonomous (Plaxco & Gross 2006).

In the late 1960s, Orgel, Crick, Sagan, Woese and others were wrestling with the 'chicken and egg' problem of the origins of life. It was known that proteins were needed for catalysis of cellular chemistry, but DNA had the genetic information to make proteins, but proteins were made by DNA! It was another twenty years before a self-replicating, single strand RNA molecule was found (in a protozoan) demonstrating that it was possible that a self-replicating system based on RNA could have been the progenitor of life on Earth (Mills & Kenyon 1996). This is water-based chemistry though, as DNA and RNA require liquid water for their chemistry (AstrBioweb), and water is the key to searching for life as we know it.

The difficulty of definition is in part, due to the fact that we only have one example of life – Earth-bound chemistry conducted with a handful of known proteins, in warm, liquid water. All known life derives from amino acid and nucleotide polymers (Plaxco & Gross 2006), but a more meaningful definition may be forthcoming when we go looking for life in the Solar System, and detect the chemical markers of an extra-terrestrial life form with similar (or not so similar) characteristics. Perhaps the most useful, though paradoxically vague, definition was proposed by Orgel (1975), a prebiotic chemist who labelled life as "Complex Information Transforming Reproducing Objects that Evolve by Natural Selection" (CITROENS) (in Raulin 2010). Dawkins (2009) says "The difference between life and non-life is a matter not of substance, but of *information*. Living things contain prodigious quantities of information.", but it's hard to build a probe for 'information' – isn't it?

An incorrect definition can cause an otherwise potentially successful expedition to fail. This was highlighted in 2007, when Schulze-Makuch and Houtkooper exposed a flaw in the definition of life used by NASA's Viking mission to Mars. The probe tested Martian soil for organic compounds which would be markers that living organisms had metabolised CO_2, but the experiment neglected the fact that some terrestrial cells contain H_2O_2 which can breakdown the resultant organic products. If Martian cells contained H_2O_2, then any molecular signs of cellular metabolism may have been destroyed by the wetting and heating process used by the probe during analysis (Zimmer 2007). Since, at the right concentration, H_2O_2 doesn't freeze until -70°, and even then it doesn't form into crystals (Schulze-Makuch 2007), and even absorbs some H_2O water in it, there's reason to speculate that an alien life form might be based on a different chemistry altogether – perhaps based on silicon and oxygen (Grinspoon 2007).

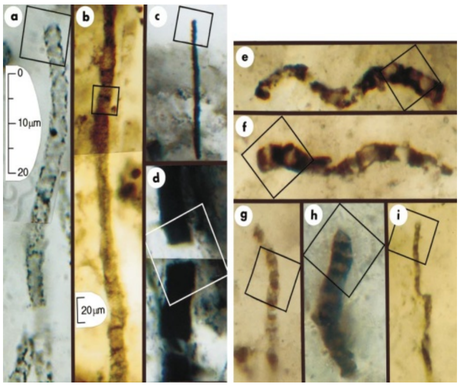
Also, defining life by listing characteristics of the only known version of it, is seriously flawed logic. NASA Astrobiology Institute's Cleland and Chyba, pointed out this flaw recently, and instead, offered that we need a *theory* of life which allows for the instance of the type we know about, but also doesn't exclude any as yet unknown varieties (Zimmer 2007). This clearly makes it difficult to design testing apparatuses which could be used to detect extra-terrestrial life.

In the early 20th century, Oparin and Haldane independently developed the idea that the chemical soup of early Earth gradually became more complex. Oparin's source of carbon was from atmospheric CH_4, whereas Haldane's was from CO_2, and they differed in their view of what provided the energy – spontaneous complexity and evolution for Oparin, and UV light for Haldane. But both agreed that the atmosphere was oxygen poor - reduced. How did a reduced environment of simple chemicals become more complex? Miller and Urey (1973) provided a possible answer in their watershed experiment which supplied an electric discharge via tungsten electrodes, to a chamber containing CH_4, NH_3, H_2 and H_2O, part of an apparatus simulating conditions on early Earth. They discovered amino acids, sugars and other organic species had been produced after only few days (DarlingMUweb). But this process may not be necessarily required.

The contemporary view about the origins of complex chemistry on Earth, includes the understanding that tonnes of polycyclic aromatic hydrocarbons (large molecules with more than one benzene ring) arrive on our planet each day from meteorites. From 2003, the Spitzer space telescope has been mapping these "…most abundant organic chemicals in the universe…" with IR fluorescence techniques (Allamandola 2009). PAHs are chemically accessible, and it's therefore quite easy to see how Earth's pre-biotic 'soup' could have developed thence. This is especially interesting given the recent discovery of Na_2SO_4 minerals on Mars and Europa, and the subsequent use of Na_2SO_4 to help identify aromatic amino acids such as phenylalanine, tyrosine and tryptophan (Richardson et al 1009).

(Fig. 1 Part of the Murchison meteorite
© New England Meteoritical Services)

It is also well understood that life processes on Earth nearly always produce 'left handed' amino acids, and 'right handed' carbohydrates in preference to their mirror-image molecular isomers (Levin 2006) – a molecule's 'chirality' (handedness) is curiously one-sided on Earth. Observed to fall in 1969 (USGSMeteoriteweb1), the 100Kg Murchison meteorite (Fig. 1) contained the first known occurrence of amino acids in the interior of a carbonaceous chondritic meteorite, that did not have equal amounts of left and right handed isomers – an indication that the meteorite contained biogenic amino acids which must have therefore come from elsewhere in the Solar System (Kvenvolden et al 1970).



(Fig. 2 Optical photomicrographs of
Primaevifilum amoenum, © Schopf et al)

Exactly when, where and how complex, pre-biotic chemistry became life, is not known, but researchers are looking at the oldest, simplest and most extreme life forms on earth to get some clues. What is considered to be the Last Universal Common Ancestor (LUCA) of all life on Earth, (Fig. 2) the cyanobacteria which built the stromatolites off the coast of Western Australia, are about 3.5 billion years old (Schopf et al 2002), and the oldest evidence of life is found in rocks from the island of Akilia, Greenland, which are 3.86 billion years old (Mojzsis & Arrhenius 1996). For the billion years before this time, the (Hadean Epoch) Earth was still forming, and receiving heavy bombardment from space, "…probably bringing microbial life…" from the young Solar System (Joseph 2009), and possibly finding somewhere to live in ancient waterways proposed to have existed as early as 4.4 billion years ago (Wilde et al 2001, Mojzsis et al 2001). It's reasonable to speculate that life could arise and/or arrive, very soon after the formation of a terrestrial planet, be subject to extinction from subsequent meteorite bombardment, and re-establish itself in later eras.

Notwithstanding our befuddled handle on what life is, it's instructive to briefly look at the origin and development of the only known version. A compressed history of the biological universe begins with the Big Bang, after which a somewhat inhomogeneous distribution of matter lead to protons colliding with other protons to form He atoms in the nuclear reactors known as stars. Anthropic biases aside, we may be suitably surprised or grateful, that the probability of two He atoms colliding to produce a Be atom is quite unremarkable considering the amounts of kinetic energy involved, but the probability of three He atoms colliding at once to produce a carbon atom, is low, carbon then becoming the first stable, fusion reaction, atom (Plaxco & Gross 2006).

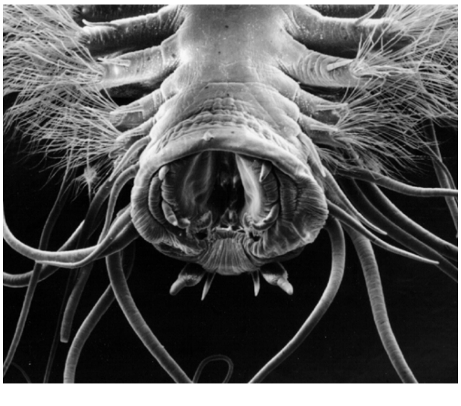
In order for carbon based life to appear, first you need carbon, and the size, metalicity, stability and position in the Galactic Habitable Zone, of our Sun, is another basic requirement for life to have evolved on Earth. Lineweaver et al (2004) showed that a region with suitable primary stars, sufficient heavy materials for terrestrial planets to form, time for Darwinian evolution, and absence of contra-indicators like supernovae, exists at around 8 kpc from galactic centre, but that when enough extra-solar planets have been discovered, a better approximation could be made.

Zooming in further to our Solar System, Earth resides in a Solar Habitable Zone with certain features that are clearly pre-requisite for our type of life. Though our planet has a crust of refractory silicates which aren't conducive to carbon life forms, conditions are such that we did evolve, presumably from a pre-biotic chemistry supported by warm temperatures thanks to tectonic and tidal friction and chemical and nuclear reactions in the Earth's interior. There's plenty of water thanks to ancient interstellar water re-delivered via outgassing (Frankland 2010), asteroid or comet delivery (Mäkinen et al 2001), and global atmospheric chemistry, and there has been a long period absent of meteoroid impact due largely to Jupiter's gravitational vacuuming effect. This interplay of cosmic physics has resulted in our Earth being the only place we *know* to harbour life.

From a recent researcher in astrobiology and Titan: The universality of carbon, along with its ability to form "structural, catalytic and informational macromolecules" with other elements, makes it a clear winner in the 'life chemistry' stakes, however, "chemical disequilibria are required to fuel the maintenance and growth of organisms" and the environment of Titan meets the absolute requirements for life, which include thermodynamic disequilibrium, abundant carbon containing molecules and heteroatoms, and a fluid environment – further concluding that "this makes inescapable the conclusion that if life is an intrinsic property of chemical reactivity, life should exist on Titan." (Baross et al 2007, Baross 2006). Life is…complicated.

University of Colorado philosophy lecturer Carol Cleland recently said in an interview with Seed Magazine: "When you go into outer space, you're going to find weird physical systems…Some of them are going to be living, but a lot of them are going to be non-living. There are lots and lots of phenomena discovered on Mars and Titan that nobody has been able to figure out. So we're going to be running into weird stuff period when we go to other worlds. The most important thing is to search for anomalies." (Zimmer 2007). Supporting the 'anomalies' approach, we find more and more are being found here on Earth.

Until recently, there were just three known ways that an organism could produce oxygen: by photosynthesis, by chlorate respiration, and by ameliorating reactive oxides. But earlier this year, a team of 23 scientists discovered that the bacterium *Methylomirabilis oxyfera* could use nitrogen oxides to convert CH_4 into O_2. Since the early Earth had nitrates available, then it's possible oxygen was also then made accessible to organisms which couldn't survive in a reduced atmosphere (Ettwig et al 2010).



(Fig. 3 Polychaete worm CH_4 eater © Chuck Fisher)

The genesis of life anywhere in the Cosmos is a thorny question at best, and even mainstream scientists have 'shown' that it's possible that life reached our Solar System with deliberate (!?) intent from intelligent aliens (dubbed Directed Panspermia), transported here as micro-organisms (Crick & Orgel 1973). And as recently as April this year, Gibson et al (2010) say the question of the origins of the universe, and life, are "resolved by hydro-gravitational dynamics (HGD) cosmology". But recent pragmatic efforts have been directed at finding out if *our* life exists, or existed, elsewhere in the Solar System.

And our type of life can also be pretty ‘anomalous’. Above, is a close-up shot of a worm which feeds on the CH_4 trapped inside ice molecules at the bottom of the Gulf of Mexico (CH_4Wormweb). Could this be a descendant of an extra-terrestrial life form?

Another extremeophile found on Earth, is a bacterium found 3.5 Km below the crust at temperatures exceeding 137^0 C (Ward & Brownlee 2000). Yet another was found in 2009: a small *Lyssianasid* amphipod discovered under 180m of ice below the Ross Ice Shelf in Antarctica (NASAEOweb). Until recently, it was assumed that while unicellular organisms have been found living in completely anoxic conditions, multicellular life could not survive a whole life cycle without coming into an aerobic environment at some stage. Even this theory has been challenged by the recent discovery of a number of metazoan (multicellular) species living in deep, anoxic, hypersaline environment at the bottom of the Mediterranean Sea (Danovaro et al 2010)

A most dramatic extreme ecology was discovered in 1976 in the region of deep sea hydrothermal vents (Lonsdale 1977). As the name suggests, these communities exist at amazing depths (as much as 5000m as reported by Showstack, 2010) and pressures, near the vents spewing hot, acidic, sulphurous, heavy metal laden, water in complete darkness, eking out a living in an ‘alien’ manner. Topping the ‘dramatic’ stakes, are bacteria living in sub-sea oil wells, and the recent discovery of a thriving microbial ecology in a hot asphalt lake in Trinidad and Tobago (Schulze-Makuch et al 2010), lending serious weight to Cleland’s call for anomaly awareness!

So, Where is Solar System Life?

Other than on Earth, at least nine other Solar System bodies have piqued the interest of scientists. And they’re not all rocky terrestrials. We should consider the planets immediately either side of Earth (Venus and Mars) because they may once have been in the habitable zone. We should look at our closest neighbour, the Moon because it has water ice and is in a habitable zone. And we should look at some of the outer Solar System moons (Triton, Enceladus, Europa, Ganymede and Callisto) because they may/have large bodies of liquid above or below ice.

We have a grab-bag of concepts about life as we know it: a generic definition from Orgel, some bio-indicators of ‘our’ life from Kasting, a four-fold list of world types from Lammer, and an anomaly alert from Cleland. However, we also know life doesn’t *necessarily* need sunlight or oxygen or water, and can exist under extreme pressures, temperatures, salinities, radiation and acidities. So, where in the Solar System do we look? Earth is the only planet in our local habitable zone, but there are niches of possible environments that have been sought out and discovered, within our Solar System, where Earth-like, or alien life, may have developed in the past and/or be extant. “Following the water”, or not, some tantalizing clues are presented here, starting from the inner most planet, Mercury, and working outwards through the Solar System…

1. Mercury

Chant (1935) discussed the 1924 and 1937 solar transits of Mercury with respect to their determination of an atmosphere on that planet, and today we have evidence from NASA’s JPL Goldstone radio telescope and the VLA, that despite a tenuous atmosphere, there is probably water ice deep inside shaded craters near Mercury’s north pole (Slade et al 1991). With temperatures as low as 125K, the same result was obtained by the same team in 1994, for Mercury’s south pole, these scans from Earth looking at parts of Mercury which were not photographed by NASA’s Mariner 10 probe in 1974/5 (NRAOweb).

Although NASA’s MESSENGER flybys have shown evidence of surprisingly large amounts of water in Mercury’s exosphere (Planetaryweb), and that it is volcanically active, Mercury has not furnished any significant clues for the existence of life. Watch this space for more telemetry about Mercury from MESSENGER, when it arrives for its orbital insertion on 18th March, 2011 (NASASolarSystemweb).

2. Venus

Again, looking for an atmosphere, this time around Venus, early scientists began by observing solar transits, and speculating about life on Earth's so-called sister planet (Proctor 1870, Arrhenius 1907). We now know that Venus has a runaway greenhouse atmosphere with nearly a hundred times Earth's pressure at ground level, and almost entirely made up of CO_2. But, could life have developed on Venus early in the Solar System's growth, when it was cooler and presumably had water on its surface?

Life may even exist in the vitriolic, UV irradiated atmosphere of Venus. Where radiation would kill otherwise unprotected species, a life form might be able to harvest sulphur from the acidic atmosphere to protect it from the harmful effects of the UV radiation (Schulze-Makuch 2004), and they may even spread to Earth from there, by Solar winds (Konesky 2009).

This question was addressed by Schulze-Makuch and Irwin (2002) who postulate that life may have retreated to the Venusian clouds when conditions became too severe on the surface. They concluded from Russian Venera, and NASA Pioneer and Magellan telemetry, that the co-existence of H_2S and SO_2, as well as the unusual absence of CO, could be explained by bacterial metabolism after a similar fashion to known Earth systems. They also considered that microbes may be able to use atmospheric sulphur compounds for their energy source, and also as a protection film against damaging UV light in the Venusian atmosphere. It is also conceivable that ultra violet light might be used by some life forms to drive a photosynthesis-like process (DarlingVenusweb). Again, watch this space for developments, especially from the European Space Agency's Venus Express probe, which is in orbit around Venus now, and as of 27th March, was operating within normal parameters (ESAVenusExpressweb)

3. The Moon

In the General Notes of Popular Astronomy magazine (Payne, 1906) the publisher states: "The evidences which seem to point to the possibility that there still may be some life on the cold and desolate surface of the Moon are variable spots that are not shadows. In these spots it is claimed that there are evidences of vegetation…..The advances which have recently been made in selenography [mapping the Moon's surface] by Professor Pickering show that although the Moon is not a riotously luxuriant abode, it is anything but the lifeless orb commonly supposed. It may be desolate and cold, but it is not altogether dead." Some decades later, in 1935, the New York Sun newspaper ran a hoax story about 'bat men' living on the Moon, that had the eventual effect of quadrupling their circulation (eTelescopeweb). Given that the twelve human astronauts who've been to the Moon didn't see any trees or bat men, and that the subsequent intensive scientific scrutiny of the Moon has returned little by way of identifiable life forms, we can probably conclude that early 1900s exobiology was a little immature.

However, current theories of planetary science don't exclude the possibility of there being some form of life on the Moon, particularly considering its proximity to Earth and the recent discovery of large amounts of water ice. Despite romantic musings about life on the Moon, the serious science of astrobiology has a bit to say about the potential for life on our Moon. Finding water is the target objective.

In 1999, NASA's Lunar Prospector detected signatures of water at the north and south poles of the Moon, and a decade later the LCROSS mission slammed an impactor into the 28m wide Cabeus crater at the south pole, sending ejecta 1 Km above the surface. Spectrometers onboard the shepherding part of the probe looked for signs of solid water ice, liquid water and OH- ions in the subsequent plume (LCROSSweb). Although confidence is high amongst researchers that large quantities of frozen water ice exist in the shadows of lunar craters, it's not 100% proven until further studies have been done (Gibson & Pillinger 2010).

The Indian Space Research Organisation launched its Chandrayaan 1 probe late in 2008, and it functioned for a year before contact was lost, but it did provide some interesting data on the chemical makeup of the Moon's surface, including at one point, a claim that organic species had been found on the surface (DNAIndiaweb). This was not later, confirmed, but it does ring true with claims of amino acids found in samples returned by Apollo lunar missions, though there's significant doubt here, due to the possibility of transformation of lunar soils by spaceship rocket exhaust, and the already understood mechanism of solar wind implantation (Hamilton & Nagy 1975).

4. Mars

In the second half of the 19th century, Schiaparelli and others, discussed the origin of supposed 'canals' on Mars and the possibility of intelligent life there. Mars has held a fascination for centuries and it has certainly been the focus of many missions in contemporary space exploration. Since it has had much coverage elsewhere, a summary of some recent Martian science as it relates to the search for life, is presented here.

In 1972, Mariner 9 pictures of ancient river beds, posed the idea that life may have existed on Mars (Marinerweb). Later, Viking missions conducted experiments to look for microbial evidence of life, finding abundant biological building elements in the Martian soil and atmosphere, but no organic compounds in the soil. Though the thin Martian atmosphere offers little protection from UV radiation, and is very oxidising, Viking did find proof of the presence of water vapour and ice, but no liquid except in the distant past, around 0.5 to 2.5 billion years ago. Mission specialists were forced to conclude that if life was extant on Mars, it hadn't been found yet (Mazur et al 1978).

The European Space Agency's Mars Express (since 2003) and NASA's Mars Reconnaissance Orbiter (since 2005) both have mission tasks of looking for extant, and past, water on Mars (MROweb). Also, NASA's Phoenix Mars lander arrived at a high 'Arctic' latitude in 2008, and was "…designed to study the history of water and search for complex organic molecules in the ice-rich soil of the Martian arctic…". It is looking at promising locations found by Mars Odyssey (since 2001), and has a robotic arm for collecting samples which can be pre-heated in small, onboard ovens. Phoenix has a 2m tall mast with camera atop, for high resolution photography of local geology, spectroscopes, and scanners to study the fog, dust and clouds up to an altitude of 20 Km (Phoenixweb).

In mid 1976, NASA's Viking probes were sent to Mars, mainly to answer two specific questions: "Are we alone or are there other living things out there? Might there have been other living things out there sometime in the past?" Soil samples collected by the landers were examined for signs of biological respiration, but interesting results eventually proved to be inconclusive, as noted above (NASAVikingweb). The resultant current paradigm is that Mars once had bodies of flowing water and probably life, but is now a dry, desolate planet with as-yet undetected life-signs. But in 2006, Levin proposed a suite of three experiments, including a modified version of the compromised Labelled Response experiment originally carried out by Viking, which he urges, will return definitive results of this important research (Levin 2006).

Mars Pathfinder was the first mission to deliver a roving science laboratory to Mars. It was targeted for a rocky flood plain in the Northern Hemisphere where good geological samples could be found. As well as many weather observations, this mission returned billions of bits of information, over 16,500 images from the lander, and 550 images from its rover named Sojourner. On its 100m travels, Sojourner covered about 250 m^2 of Martian ground (DarlingSojournerweb), made 15 rock/soil analyses for chemical composition, and overall results show Mars to once have had liquid water on its surface and a warmer, thicker atmosphere (Pathfinderweb). Rounded pebbles in silt, landforms reminiscent of river riverbeds, ancient mudflows near the equator, water permafrost under the polar caps, and iron oxides similar to those produced on Earth in wet environments all point to extant, and past water on Mars (NASAGISSweb).

In the next successful mission to Mars, NASA sent two rovers named Spirit and Opportunity, to opposite sides of the planet. Arriving within weeks of each other in 2004, Spirit landed at Gusev Crater, a large impact crater which may have been flooded in the past, and Opportunity landed in a small, equatorial crater on Meridiani Planum, (SpiritOppweb, UCARGusevweb, UCARMeridianiweb). The main tools onboard Spirit and Opportunity, which have provided hundreds of thousands of pictures, thousands of spectra, and allowed scientists to formulate theories about how Martian geology developed, are the panoramic camera, a thermal emission spectrometer to take an atmospheric temperature profile, a Mössbauer spectrometer to look at rocks/soils with Iron content, an Alpha particle X-Ray spectrometer to look at elemental rock makeup, magnets to collect particles for analysis by the spectrometers, a camera for high resolution, microscopic close-ups of rocks and soil, and an abrasion tool for grinding away rock surfaces for inspection (MERMissionweb). All this in an effort to achieve the overarching mission aims to characterise the Martian soil, rocks and geology with respect to the activity of water in the past, and conditions for life (MEROverviewweb).

Perhaps the discovery that won the ‘popular science’ stakes, was Opportunities quaintly dubbed ‘blue berries’ which are spherules largely made of hematite – an iron oxide that requires the presence of water for formation (JPLMERweb).

Allen et al (2001) had emphasised the importance of rovers’ landing sites being near hematite, an iron oxide associated with water deposits and bio-indicators. A 2004 NASA view of Mars is a planet of basaltic rock, with sulphuric acid groundwater which interacts with the rock, dissolving things out of it, which then evaporate, leaving sulphate salts like $MgSO_4$, behind, sometimes resulting in sulphate-rich evaporation beds such as those at Meridiani (Spaceweb). Squyres et al (2007) reported on sulphate rich sandstone and bedrock, and wind erosion around Victoria crater, observed by Opportunity, and eroded basalt and silica-rich soils at Home Plate by Spirit, speculating that life may have existed. One of Spirit’s wheels jammed four years ago, and dragged across the soil, revealing salts just beneath the surface, which were formed in the presence of water, so scientists think Mars once had lots of water which evaporated and left these salts. The soft, powdery topsoil eventually bogged Spirit which is now a stationary science platform (Spiritvidweb).

Opportunity and Spirit have been on Mars for six years, and have travelled over 20 Km and 7.7 Km respectively (MERMissionweb, MERSpiritweb). The ability to traverse the surface shaped the design of some of the science carried out. For example, studying landing sites, rocks and soils showing potential liquid water chemistry and/or pre-biotic activity as well as the types, morphologies, textures, distributions and chemistry of rocks and soils. Also, as the missions surpassed their expected lifespan, atmospheric telemetry was able to describe the Martian seasons over several years (Starbrightweb).

The continued presence of seasonally varying levels of CH_4 in the Martian atmosphere also is suggestive of a biological process, similar to terrestrial microbial action which can make CH_4 from H_2 and CO_2 in the soil (MarsMethaneweb). Krasnopolsky (2006) presented an exhaustive study of CH_4 plumes on Mars, favouring biological production as the cause, and the ESA ExoMars Orbiter mission planned for 2016 will have this science high on its list of aims (MSSLweb).

Mars Reconnaissance Orbiter, Mars Exploration Rovers, Phoenix and Mars Global Surveyor missions have all shown supporting telemetry for large bodies of water, even an ocean, in the northern hemisphere, on Mars in the past (Becker et al 2010), and all missions have confirmed that water did once flow on Mars.

Scientists on Earth know enough about the atmosphere of Mars (and Titan) to design and conduct an astrobiology chamber which simulates Martian atmospheric conditions, in order to study the effect on bacteria (Muller & Ward 2010). Again, watch this space!

5. Jovians and their Moons

The larger satellites of the gas giants probably formed at the same time as their parent planets, and would normally be thought to be too cold to support life, but tidal flexing of these moons causes significant heat – enough to re-surface them and/or cause geysers. Where there's heat, is there life?

Amongst the many speculations offered about the form that other life might take, are Sagan and Salpeter's calculations showing that there is a biological niche in Jupiter's atmosphere which could sustain an ecology of 'floaters', 'sinkers' and 'hunters' (Sagan & Salpeter 1976). While considered fanciful today, these sorts of ideas are nonetheless part of the process of thinking about the forms that extraterrestrial life might take, in unexplored, alien environments.

Scientists have long considered the internal dynamics of the icy Galilean moons, and indeed smaller, colder moons, in attempts to explain observed surface features (Reynolds & Cassen 1979, Williams et al 1996, Moore & Schubert 2003), and the potential for life, and in mid 2003, a group of Lunar and Planetary Institute scientists got together to discuss a Jupiter Icy Moons Orbiter (JIMO) mission to "…explore the three icy moons of Jupiter – Callisto, Ganymede, and Europa…" The three objectives of JIMO were to look for signs of life, habitability, and confirmation of oceans. The orbiter was to have instrumentation specifically designed to detect CO_2, CH_4, H_2O, NH_3, H_2S, NO_3^-, NH_4^+, HPO_4^{2+}, lipids, carbohydrates, proteins, nucleic acids, fluorescent co-factors, alkalinity, salinity, pH and much more, all biogenic and/or bio-indicators. It was to also look for evidence of tectonics, cratering, magma, and other characteristics of active, potentially biological worlds. The program didn't make it past early planning stages, but does indicate the direction in which the search for life in the outer Solar System, might go (JIMOweb).

Largely from the Voyager and Galileo mission results, we know that Jupiter's moon Europa has plenty of carbon, nitrogen and phosphorous, a source of energy from gravitational flexing of the mantle, and enough water (probably) for biological processes to develop. And oceans made salty with Mg^{+2}, SO_4^{-2}, Na^{+1} and H^{+1} may be complicated by organisms which extract various elements for construction of their bodies, or metabolise sulphur for their energy (as some do on Earth), so spectrographic analysis has to be carefully married with geological theory before serious predictions can be made (Europaweb). Magnetometer readings from Galileo specifically suggest a planet-wide layer of conducting fluid on Europa, but also suggest liquid water layers on Calisto and Ganymede, sandwiched between ice layers (Space1web).

The Galileo mission ended on 21 September 2003. The spacecraft's systems had suffered irreparable radiation damage after a series of close fly-bys of Jupiter's moons Europa and Io, later in its life. Galileo's propellant was almost depleted and the spacecraft was put on a collision course with Jupiter. The probe flew at Jupiter's atmosphere at 180,000 km/h. It was decided to destroy Galileo in this way so as to minimise the chances of any contamination of Jupiter's moons with bacteria from Earth. In particular, an impact with the satellite Europa, which is thought to be one of the best candidates for hosting life, had to be avoided.

Providing The Monolith of Space Odyssey fame doesn't interfere, closer examination of Europa may prove fruitful in the search for life. Shallow craters, strange criss-cross surface markings and cracks where upwelling occurs, all hint at Europa being covered by ice (NASAGalileoweb). A deduced sub-surface ocean 100 to 200 Km deep would contain dissolved salts, and probably heated by thermal vents created by tidal flexing due to Europa's proximity to Jupiter's gravitational field. This ocean may even contain oxygen derived from the ice, having been liberated by Jupiter's strong magnetosphere radiation, and perhaps not be too hostile to a life form (DarlingEuropaweb).

Two of Jupiter's other moons, Ganymede and Callisto, have probably got similar subsurface oceans, and these worlds are targets for future missions (AstroRoadmapweb), and scientists are already developing mission objectives and plans for outer Solar System exploration because of the clues to life which may be found (McKinnon & Johnson 2009). Because a similar environment exists on Earth at the subsurface Lake Vostok, near the south pole (NASAsciweb), designs for a 'cryobot' mission can be physically tested ahead of time (Shylaja 1997).

McKinnon and Johnson (2009) have outlined a strategy for exploring the outer Solar System over the next decade because according to them "…the outer solar system provides critical clues to unraveling the mysteries… of how life has evolved…”. As well as continuing support for Cassini and Juno (arrival at Jupiter aimed for 2016), they see an observation mission to Io, an in-situ probe to Titan, and further study of Neptune, Triton and other KBOs, as a high priority. Baross et al (2007) would agree, believing that “…the environment of Titan meets the absolute requirements for life, which include thermodynamic disequilibrium, abundant carbon containing molecules and heteroatoms, and a fluid environment … this makes inescapable the conclusion that if life is an intrinsic property of chemical reactivity, life should exist on Titan.”

In 2004, NASA’s Cassini-Huygens mission described a methane/ethane atmospheric cycle on Titan which is very similar to Earth’s hydrologic cycle, taking pictures of hydrocarbon lakes near Titan’s north pole (AstroMagweb). Given that we have microbial ecologies in asphalt here on Earth, life on Titan cannot be ruled out.

Enceladus, Triton and Titan are the only moons which have enough cryovolcanic activity to create an atmosphere (Tobie et al 2010), feeding ideas about life in these far-off atmospheres. Lellouch et al (2010) recently confirmed Voyager 2’s 1989 detection of CH_4 on Neptune’s largest moon Triton, as well as detecting CO. Comparison of partial pressures, and with Voyager’s measurements, reveals a seasonality on Triton, so the possibility of finding life there isn’t such an outrageous concept.

Triton was the first active, icy satellite discovered, and Hurford et al (2009) subsequently reported that the interesting surface spotted by Voyager, on Enceladus, a moon in Saturn’s E-ring, is still active with cryovolcanism. The Cassini probe has since recorded gas and ice spewing from warm cracks near the moon’s south pole, and this ice is probably maintaining Saturn’s E-ring. They go on to say: “…the plume source region on Enceladus samples a warm, chemically rich, environment that may facilitate complex organic chemistry and biological processes…”. “…Tidal heating, cryovolcanism, and ice tectonism…” are features reminiscent of those on Earth which nurtured life into existence.

6. Comets, Asteroids and Meteoroids

Some of the smaller bodies found in the Solar System may hold clues, if not life itself, and considering the important role of cometary water delivery to the forming Earth, and the frequency of impacting meteorites, these bodies are closely studied by astrobiologists. We can now hope to examine asteroids which we observe hitting the Earth, (for example 2008 TC3 (Univweb)), and even involve the public in helping scientists to find interplanetary dust particles in aerogel samples returned from missions (Stardust@homeweb).

The importance and relevance of meteorite study was re-enforced by Alexander (2009), who alluded to the discovery of non-chiral (non - “handedness”) amino, and nucleic, acids in some, as well as other geo-formation inferences drawn from examination of carbonaceous, chondritic (conglomerate type) meteorites. Carbonaceous chondrites have PAH production occurring via several aqueous, chemical pathways during the formation of the parent body of the meteorite (Wing & Bada 1991), and so are of significant interest to astrobiologists.

Of the nearly 40,000 meteorites found so far on Earth, 14 are the so-named SNC meteorites and a particular one was found in Antarctica, making headlines because of its Martian origin (from Mars (Treiman 2000, USGSMeteoriteweb2). ALH84001 was found at Allan Hills, Antarctica in 1984, and analysed by McKay et al (1996), who concluded that carbonate globules, PAHs, and other indicators were best explained by biological activity occurring on Mars. Though subsequent dating efforts produced older ages for ALH84001, Lapen et al (2010) have shown by isotope dating, that it is about 4.1 billion years old, which coincides with a heavy Martian bombardment period and with the time Mars lost its magnetic field. A string of evidence provided by orbiting Mars probes has located the area from which, 17 million years ago, ALH84001, was ejected from Mars - a crater in the Eos Chasma, part of the huge Valles Marineris canyons was identified in 2005 (NewSciweb), and arrived in Antarctica about 13,000 years ago (WolframSNCweb).

McKay et al (2009) re-examined ALH84001 and other Martian meteorites collected from widely separated areas on Earth, and showed that geological processes could definitely not explain their formation chemistry, biogenic processes being the sole remaining explanation. This begs the question: did life ‘cross contaminate’ from Mars to Earth (Hoover 2005)?

A new suite of instruments including a mass spectrometer, was developed by Stern et al last year, and they used it to identify the first ever amino acid (glycine) from a comet (collected by NASA’s six year long Stardust mission to comet 81P/Wild 2 (Burchell et al 2009)), proving with radio-isotope comparisons, their extra-terrestrial origin (Stern et al 2009). Examination of Antarctic meteorites with the same instrument has detected nucleobases, their origins yet to be confirmed.

The existence of pre-biotic amino acids on comets leads into a large sub-field of astrobiology: panspermia (or Pan-Vitalism as Lafleur originally called it (Lafleur 1941)). The idea that the seeds of life existed in space well before the formation of Earth, was promulgated in the scientific literature at least as far back as 1973 (Crick 1973). Champions of this idea have been, and are, amongst others, Fred Hoyle (of Big Bang fame) and Chandra Wickramasinghe (Director of the Cardiff University Centre for Astrobiology), the likes of whom now study interstellar dust, comets and asteroids for the chemistry of life. Very recently, the asteroid 24 Themis was found to have ice and organic compounds prevalent on its surface (Campins et al 2010)

In 1996, Henry Hsieh, astronomy student at the University of Hawai'i noticed an unusual asteroid which had the icy characteristics of a comet. He went on to publish his PhD dissertation in 2007, and proposed a new class of comets, called Main Belt Comets (MBCs) (Hsieh 2007). The inference from this work, is that water delivered to Earth perhaps in the Late Heavy Bombardment period, may have come from these MBCs and therefore studying their chemical makeup and comparing it to Earth’s oceans, may reveal more information about the origins of life on Earth (Hsiehweb). This is a new and exciting field of study.

Conclusion

To search for life in the Solar System, we first need to know what life is. We have some known characteristics of terrestrial life, such as self replicating, evolving chemical systems which can derive energy from diverse, sometimes extreme sources. Based on carbon, and requiring liquid water, life as we know it may have been seeded from space, subsequently acquiring its unique left-handedness and genetic format.

The discovery and study of extremophiles, and our lack of a ‘theory of life’, indicates our need to be on the alert for anomalous chemistry when exploring space. We might just stumble across a new type of life, or an otherwise unsuspected version of the familiar type. Most of the larger bodies in the Solar System have at least the theoretical possibility of life, or its precursors. So, apportioning funds to sink into missions will be an ongoing discussion amongst astronomers.

One could identify three broad aspects to the search for extra terrestrial life in the Solar System. *Speculative* life forms could be searched for, but human imagination is an expensive criterion on which to base a billion dollar exploration mission. Speculation is, however, a valuable breeding ground for ideas which may subsequently come to fruition. We could search for *anomalies* which may appear in the due course of exploring the Solar System, and we can investigate their causes, which may turn out to be biogenic. Anomalies are, by definition, difficult to spot. Or we could proceed from *theory*, and look for specific bio-markers which may indicate the presence of biological processes – exotic and familiar.

Perhaps all three modes are/should be, mingled into all efforts. Speculation is healthy and may keep us alert to anomalies which after all, would, by definition, always be anathema to an existing paradigm, because when searching unknown territory we’re constantly finding new physics, biology and chemistry. And we clearly need a theory of life from which to distinguish these anomalies, but also to guide our search for Earth-like life.

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