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Introduction

Fred Hoyle, a late British astronomer, once said that the emergence of a single basic cell from the primordial soup of Earth had same probability of "a tornado sweeping through a junk-yard might assemble a Boeing 747 from the materials therein" (Rampelotto, 2009). Hoyle's theory was that Earth was seeded with Life from space, also known as the Panspermia Theory. The universe is an extremely large place, with billions upon billions of planets. Consequently, it is unlikely that Earth is the only planet in the universe to have developed life, let alone intelligent life. Discovery of life that has evolved independently from Earth within our Solar System would lead to an assumption that life is common within the universe. Furthermore, provided that intelligent life on Earth evolved from microbial life, the same process could potentially occur on other planets, and intelligent life could also exist elsewhere in the universe. Thus, we would not be alone.

Discovering life that is identical or very similar to microbial life on Earth on another body in our solar system would partly enable us to answer the question of where life on Earth came from. Based on what we know of microbial life on Earth, this paper will discuss what microbial life is, how we can detect microbial life, where in the Solar System life could exist or has existed, and what evidence has been found for and against it so far in the Solar System.

What is Microbial Life and how to detect it?

Microbial life or microbes, are the oldest form of life found on Earth. Microbial life are mostly single cell organisms and small enough not be detectable by the naked human eye. Microbes come from all different kingdoms of life, from bacteria, fungus, plants and simple animals, e.g. plankton.

The general consensus on the definition of life, based on observations on Earth, which constitutes our only observable source of life, includes the following (Cleland & Chyba, 2002; AstrobioWeb):

- Reproduction: Living organisms reproduce. Either asexually or sexually. Asexual is where the parent split their own body to form new children. Sexual reproduction is the creation of a new single cell organism that will grow into an adult organism.
- Metabolism : Life processes energy to survive, either via absorption of materials or energy (such as photosynthesis)
- Stimuli : Organisms react to outside stimuli. This can take the form of reaction to chemical, heat, light or even more complicated reactions that multicellular animals perform.
- Evolution : A living organism can mutate. New generations will not be identical to previous generations over a large enough sample size.
- Homeostasis : An organism tries to maintain its internal environment at an equal temperature.

These are the five most common attributes of life on Earth. By applying these criteria, we can eliminate non-organic forms that may simulate life on Earth. If it can be determined that an organism possesses all 5 of these attributes, it can then be safely concluded that this is a form of life. Detecting advanced multi-cellular life is much easier than determining whether an organism is a microbial life, as it normally includes just single cell organisms.

In order to understand the process of reproduction, close observation is required, and in the case of microbial life, it involves observation at the cellular level.

Metabolism is the easiest to detect. This can be accomplished by introducing nutrients into the environment that would then produce waste chemicals if a microbe was processing it. By changing the environment around suspected areas of microbial life, and observing what happens is also a good test. By removing or adding nutrients, different chemicals should be released as organisms live and die. Furthermore, there exist remote methods to search for evidence of metabolism by analysing the spectrum of planets to see the chemical composition, which makes finding organic compounds possible.

Similar tests can be performed to discover the stimuli the affects different forms of life. Since all living organisms required energy, by removing their energy source, whether material, chemical or other energy source, their reaction, such as movement or irregularity in the reproductive cycle, can be observed. Finally, applying heat or cold also represents a good primary test for detecting reaction to stimuli.

Similar to reproduction, evolution requires observation, if evolution can be observed in an organism, then it will be the final definite proof needed to declare the discovery of life.

Finally homeostasis. This might be the easiest to detect an area of a planetoid to further investigate. Even a minimal temperature difference of a few degrees between an area and its surroundings, with no non-biological explanation, could suggest that there is some form of life regulating its internal temperature. While not proving the existence of life, it can highlight a specific area for further investigation, and imply that further test are required.

Most of these all require detailed observation, and thus, building a robot or remote tool to perform these tasks on a distant planet is very difficult. Since life on other worlds may differ vastly from that on Earth, it requires human intelligence to observe, test and try unusual methods of detection.

The above methods cover detection of extant life, and will not suffice when searching for evidence of extinct microbial life. There is a distinct possibility that microbial life once flourished in our Solar System, however only faint evidence may remain. None of the above tests will work on dead organic matter. McKay (2008) argues that if we find pattern of organic molecules similar to that which we have found on Earth, this would indicate the material is of biological origin. The main criticisms of this theory lie in the fact that there often exists a similar non-organic method of constructing these molecules. In response to this critique, McKay (2008) suggests that organic life is primary made up of left handed amino acids(L) much more than right handed amino acids(D). The difference between L and D can be detected in the 3-dimensional representation of the amino acid, as one protein looks like a left hand, the other a right. As a result, if material consisting of primarily left handed amino acids were discovered it would be more likely to be organic than chemical in creation, similar to biological material on

Earth. A 50/50 split, however, would suggest it was a chemical reaction. Therefore, unless the extinct life is a more complicated form, such as a multicellular life form, it may be difficult to prove definitively that it was once a living organism.

Habitable Zone

There exist certain zones within the solar system which are thought to be able to support different forms of life. The first is the habitable zone(HZ), which defines the range from a star where a planet can support life. This zone also moves with the age of a star. When a star is newly born, it generates less light and heat, therefore the HZ will be closer to the star. As the star becomes older, and generates more heat, the HZ will drift outwards. This means there is an area, called the continuously habitable zone, where over the majority of the life cycle of a star, life can be sustained (Ward & Brownlee, 2003). In order for life to develop, a planet needs to remain within the habitable zone for a long enough period of time.

Plate tectonics, the large scale movement of the lithosphere (the crust and upper mantle), are also thought to be needed to support life. The movement of these plates results in changes to the environment on the planet, thus increasing the probability of life developing. However, this is more important for the development of advanced forms of life. Furthermore, active volcanism is needed to prevent a complete decrease of CO_2 in the atmosphere. Active volcanoes keep the plate tectonics moving. If the plates stop, eventually the continents will be worn away by erosion, thus an ocean planet, and then via weathering, CO_2 will be dissolved in the oceans, creating a frozen planet (Ward & Brownlee, 2003).

The Microbial Habitable Zone (MHZ) is the zone of interest for microbial life and is where simple life can develop. It is believed that almost the entire solar system is within the MHZ, and thus any body in the Solar System can support microbial life if the body has the right environmental conditions (Ward & Brownlee, 2003).

What does life need to survive?

All known species of carbon based life forms require liquid water to survive. The second condition of survival is the ability to metabolise some form of energy, via the processing of materials or direct absorption of that energy.

Life in extreme conditions

By observing the way some forms of life adapt to areas of extreme environments on Earth, which constitutes our only observable source of life, these conditions can be matched up to areas within the Solar System with similar conditions.

Under the Taylor Glacier, microbes have been found that survive with no heat, light or oxygen.

These microbes recycle sulphates for energy. If these microbes were transported to another planet with a source of sulphates and liquid water, they would survive (Bidle et al 2007). In the reactor of Chernobyl, some forms of fungi have developed, that use the radiation left behind in the reactor, for their energy source. (CosmosWeb). A more advanced form of multicellular life has recently been discovered beneath the seabed of the Mediterranean, that does not require oxygen to survive (Danovaro et al. 2010). Tardigrades, also known as water bears, have been taken up into space, released into vacuum and known to survive, albeit they do not seem to be able to reproduce in a vacuum (Jönsson et al. 2008). These examples demonstrate that life flourishes even in extreme conditions on Earth, adapting to use whatever resources are available to survive. Furthermore, new forms of life can develop in extreme environments.

How did life start on Earth?

The basic structure of life is Deoxyribonucleic acid (DNA). Part of working out how life started, whether on Earth or elsewhere in the universe, is establishing how to create DNA. DNA requires a few ingredients such as energy and amino acids, as well as the right environment and conditions (Ward & Brownlee, 2003).

Many scientists agree that all life on Earth originates from a common ancestor (ScienceNewsWeb). By analysing different proteins amongst current species and then running computer simulations to see how various evolutionary scenarios would impact what is currently observed. Theobald (2010) ran these simulations and found that the probability life evolved from a common ancestor was much higher than that of life developing from multiple ancestors.

In the lab there have been numerous experiments aimed at recreating the conditions of the primordial soup to create DNA. One of the most famous is the Miller & Urey experiment in 1952. In this experiment water, methane ammonia and hydrogen were mixed together, simulating the atmosphere of ancient Earth. Finally, an electric discharge simulating lightning strikes on Earth was added to the mix. The results of this experiment were a few different amino acids, which comprise the building blocks for DNA. However, after 50 years of experiments, DNA has not been able to be randomly created in the lab. The step from amino acid to DNA might require a very specific set of circumstances with a very low probability of occurring. It is highly probable that this set of circumstances, however unlikely, did arise when life was originally created (Lazcano & Bada, 2003).

Recently scientists have been able to create a synthetic bacterial cell. While the genome is almost identical to a native *Mycoplasma mycoides* genome, it was assembled using in-vitro technology, then combined using a technique called yeast homologous recombination and finally inserted into a host cell (Gibson et al, 2010). Although this process still requires a living cell, it represents a breakthrough in being able to create artificial life in the laboratory and if artificial life can be created, it is likely that elsewhere in Solar System, the right conditions may also exist.

One theory states that life was created on Earth in the primordial soup, a process that was initiated by an external energy source, such as a lightning bolt (Lazcano & Bada, 2003). The other theory is the Panspermia Theory, (Napier, Wickramasinghe, & Wickramasinghe, 2007) that argues that life on Earth came from either a meteorite or comet, striking the Earth and carrying the building blocks of life. Furthermore, Mars is thought to be a possible source of this life. A comet is also a very likely candidate, especially one with a large abundance of water. Life on Earth requires liquid water, and therefore a comet that spent a large portion of its life in the liquid stage, could have germinated life. During the early life of the solar system, there were many more comets than exist now (and even now there are new comets found every year). This could have increased the chances of life developing on at least one comet, as each would be in a different environment with regards to radiation and energy, whereas the Earth remained more stable (Napier, Wickramasinghe, & Wickramasinghe, 2007). The assumption that life on Earth did indeed come from a comet leads to a conclusion that life has existed elsewhere in the solar system. However, determining which comets are the most likely source of life is problematical, a fact that limits the opportunities to conduct the costly search for life on comets.

Mars

Mars is thought to have once held liquid water, and is one of the few bodies in the solar system that has had robotic explorers on its surface, making conducting experiments searching for life easier. The one experiment that may have found life on Mars is the Viking Lander Labeled Release experiment (LR). The LR had enough material for 9 tests. The Viking Lander dropped a solution of organic nutrients onto the soil sample and then observed if any gas was released as evidence of metabolism. As a control group, other portions of soil were heated for 3 hours at 160 ºC to sterilise the soil. If the unsterilised soil gave off gas, and the sterilised soil did not, this would suggest that existence of organisms in the soil. Gas was detected from both samples, therefore suggesting a chemical reaction and not a biological one (VikingWeb; Levin, 2007).

Despite the lack of definitive proof of the existence of extant microbial life on Mars, perhaps life once did exist on the planet. Firstly, based on what has been observed of life on Earth, life requires liquid water to survive, and therefore evidence of liquid water on Mars needs to confirmed. Judging by surface views of the planet, there exist many channels that appear to be formed by liquid water, as the flow does not match to the flow patterns of lava (NASAGISSWeb). For example a bend in a flow normally requires numerous floods of running water. Furthermore, the discovery of hematite within small spherules suggests the presence of water on Mars at some point of time. On Earth, the size and shape of the hematite usually forms in a wet environment (MarsRoverWeb). According to one theory, there exist vast reservoirs of frozen water under the surface of Mars, since the liquid water could not have evaporated in its entirety. If frozen, or even better liquid, water can be discovered on Mars, it could then contain microbial life. However, as it has not, the assumption needs to be taken it is not presently there, but as water did once exist, that means life could have existed on Mars in the past.

AHL84001 was a meteorite discovered in Antarctica in 1984. Ten years after its discovery it was determined that it originated from Mars, due to the similarities with other Martian rocks and the composition of the meteorite, such as oxygen isotopes. The original study by McKay (1996) found unusual forms of nanophase magnetite within it, similar to magnetite produced by magnetotactic bacteria on Earth (McKay et al. 1996). McKay believes this to be of biological origin. McKay also published and discussed the images of carbonate globules, that do look like nanofossils under magnification. As these are simple organisms, the carbonate globules could have formed chemically, and not be of biological origin. However, Bradley (1997) challenged this theory, arguing it was an artefact caused by the application of conductive coating, part of the scanning process. The discovery of Polycyclic Aromatic Hydrocarbons (PAHs) was another piece of evidence that McKay argues is part of a biologic process. PAHs are thought to only be created by biologic life on Earth (McKay et al. 1996). Becker, Glavin, & Bada (1997) counter that this could be a result of the melt-water in the Antarctic contaminating the original meteorite. A recent paper by McKay et al. (2009) discusses the various theories about non-biological means to create these nanophase magnetites. While McKay(2009) refutes most of these non-biological theories, all evidence of biological life from the meteorite can be created artificially in the lab without biological means, so there is no definitive answer on whether the meteor evidence is biological or chemical in nature. Likewise, the Naklha meteorites also have similar features, but again this could be an artefact of the scanning process (Keprta et al, 2009).

On Earth methane gas is normally associated with a biological source. Therefore the discovery of large quantities of methane gases on Mars could be associated with some micro-organisms (MethaneWeb). The methane gas needs to be created by an ongoing process, as the thin Mars atmosphere means the gas is soon dispersed. If life is creating the methane gas, it would need to be far beneath the surface of Mars, where liquid water could still exist. However, the methane gas could also be the result of a chemical reaction. On Earth iron oxide can be converted into the serpentine group of minerals, releasing methane gas. This process normally involves water, carbon dioxide and heat. While currently there are no active volcanoes on Mars, this process could have happened in the distant past when these methane gas pockets could have been trapped, and are only just being released now (MethaneWeb). Considering the definition of life, methane may suggest metabolism is occurring, but in order to prove life exists, we need to also show reproduction, reaction to stimuli, evolution and homoeostasis. For that reason, while the source of the methane gas on Mars is a good site for further exploration, it does not prove evidence of microbial life, but it will be a good site for further exploration. Therefore, while there is no proof of life, past or current, on Mars, there is enough arguable evidence to justify further investigation.

Titan

Titan is the largest satellite orbiting Saturn, and as the only satellite in the solar system that has a thick atmosphere (4.5 times denser than Earth's), it is a strong candidate for having microbial life. Furthermore, it possesses a methane cycle that is similar to the water cycle on Earth (Raulin, 2008). There seems to be some evidence of liquid water on the planetoid, but more interestingly there may be liquid pools of methane still on the planet, and perhaps life has developed in these pools. Finally, the Cassini instruments detected volcanic and tectonic activity. This means the moon is still active (Raulin, 2008). Also the Cassini probe detected organic compounds in the atmosphere of Titan. These could either come from an organic source, or be chemically created.

Keeping in mind the theories on the origins of life on Earth, and in reference to the Miller and Urey experiments, Titan does seem to have all three base prerequisites for the existence of life – organic matter, liquid water and energy. If life did develop on Titan, which is a strong possibility, it would vastly differ from life on Earth, as it would need to survive in a methane environment.

Comets

Comets are partly thought to be a possible source of water on Earth. In the early days of Earth's life, numerous comets are believed to have crashed into Earth, bringing with them water (Napier, Wickramasinghe, & Wickramasinghe, 2007). Furthermore, as mentioned previously, one theory on how life started on Earth, was that it was brought to Earth via a comet. However, there are a few problems with this theory, as some comets travel a highly elliptical orbit around the Sun, sometimes taking hundreds, up to thousands of years for a single orbit. Only while it is close enough to the Sun, does the comet heat up enough to have liquid water. This means life would need to have developed in the relatively short period of time that comet was in a liquid state. But due to the massive number of comets in our solar system, with each going through a different series of events with regards to radiation, environment, life, or the early building blocks of life, could have developed on a comet and then crashed into Earth. These building blocks could then be built upon on Earth.

For life to currently be existing on a comet, these forms of life would have had to adapt very quickly. Once they were first born, they would then need to evolve within a thousand years, to survive the cold reaches of the solar system. Therefore, uncovering evidence of past microbial life on a comet is more likely, but it is unlikely that we will find extant microbial life on a comet, especially considering the challenging nature of determining which comet would be the most likely candidate for a survey.

Asteroids

Recently, water ice has been found on the asteroid 24 Themis (ScientificAmericanWeb), currently in orbit around the Sun, located between Mars and Jupiter. Previously only comets were thought to contain water, as they originate from a more distant region of the Solar System. In addition organic material has also been detected on the asteroid, which proves that, similar to comets an asteroid could potentially sustain microbial life. In order for microbial life to develop on an asteroid, it needs to be located within the Habitable Zone. However, due to the small mass, this will mean there is not much of an atmosphere. Also, due to its limited size, and lack of diversity in environment perhaps the life will quickly consume all available resources. Nevertheless, some asteroids possess sufficient mass to be able to sustain life indefinitely.

Venus

While the surface of Venus is extremely hostile, the clouds above the surface could sustain microbial life. Although Venus is located within the habitable zone, the extreme heat and conditions on the surface makes it unlikely for life to develop, but the temperature in the atmosphere roughly 45km to 70km above the surface, is within the temperature ranges for life of microbial life on Earth (Wickramasinghe & Wickramasinghe, 2008). The atmosphere contains a large portion of CO_2, but also some water, and the cloud system is stable, and circulates between 45km and 70km in parts of Venus, which means an organism could survive. However, there remains the question is on how these organisms would metabolize energy. Wickramasinghe & Wickramasinghe (2008) theorise that the organisms could be subsisting on meteorites that break up in the atmosphere or they could even be processing the $CO_{2,}$ similar to plants on Earth.

Despite the possibility of life in the upper atmosphere, the extremely hostile Venusian atmosphere at lower levels is likely to limit surveys of the planet. Thus, other bodies in the Solar System are more likely candidates for exploration.

Enceladus

Enceladus is a small moon, roughly 500 km in diameter, orbiting Saturn. The Cassini space probe did several fly bys in 2005, and made a major discovery, a plume of water vapour located in the south polar regions. The discovered plume of water ice reached heights of 80km from the surface, and was much warmer than the rest of the planet, suggesting geothermic activity. Therefore Enceladus seems to have energy, liquid water and organic matter, all of the fundamentals for the existence of life (Parkinson, et al. 2008). Unlike Europa, Enceladus is not bombarded with radiation, thus increasing the possibility of microbial life.

Europa

As discussed previously, one of the key elements to life is liquid water. If water is found, the odds of finding life are greatly increased. Europa is a moon of Jupiter and while it seems far enough from the Sun that it will be frozen, the tidal forces that Jupiter exerts on it, and perhaps some geothermal heating, may keep some liquid water below the frozen surface (Webb, 2002), although the surface is covered in frozen water crust layer that may be up to 20-30 km thick. Europa is marked by many impact craters which may result in Europa having a more diverse range of chemicals compared to the other moons of Jupiter (Lipps et al. 2004).

The large amount of radiation that Jupiter exerts on Europa may have sterilised the moon, but this does mean that there still might be evidence of past life on the planet, or as we have seen on Earth (radiation eating fungi in Chernobyl reactor), life could have developed that absorbs the radiation as part of its metabolism (McKay, 2008). Furthermore, life could also have been created via the radiation that Jupiter outputs.

One of the difficulties in determining if life exists on Europa, is firstly the challenge of landing on the moon, due to the many satellites and large gravity that Jupiter exerts. The lander would also have to drill down beneath the thick crust of ice to hopefully find liquid water, before then being able to conduct any experiments. While the likelihood of life existing on Europa is high, the difficulty in conducting any experiments means exploration is not likely to occur in the near future.

Ganymede

Ganymede is a moon of Jupiter, and the largest moon in the Solar System. From NASA's Galileo probe, it is believed Ganymede also has liquid water below its surface, which is believed to be salty water at around -13ºC (Knight, 2001). This would be sufficient for life to exist (see Taylor Glacier microbes). Unlike Europa, however, Ganymede seems to be heated internally via natural radioactivity, which, combined with the radiation from Jupiter, may not be conducive to life, but there is a magnetic field around Ganymede which might mitigate some of the effects of the radiation, unlike Europa. In addition, the liquid ocean is at a lower depth than that of Europa, which may provide more protection from radiation, but it will also not obtain as much heat.

However as we have seen on Earth, microbial life can exist in extremely cold environments (Knight, 2001).

Callisto

Callisto is a moon of Jupiter, the second largest around Jupiter and third largest in the Solar System. From the Galileo mission, it is believed to have an ocean of liquid water at depths of greater than 100kms. Callisto is an older moon and does not seem to be geologically active. Nor does it experience tidal heating (Showman & Malhotra, 1999). Despite evidence of liquid water, the lack of heat compared to the other moons of Jupiter make this the least likely candidate for life out of Jupiter's Moons. However, organic compounds have been detected on the surface, which could be a form of microbial life, or evidence of metabolism (Showman & Malhotra, 1999). Callisto also does have lower radiation levels than other moons of Jupiter.

Overview of conditions for Planetary Bodies in Solar System for Microbial Life (in descending order of probability of life existing/existed)

Planetary Body	**Positives for evidence of Microbial Life**	**Negatives for Microbial Life**
Mars	+ past history of liquid water + methane + Meteorite evidence (AHL84001 and Naklha) + Viking Lander LR + Was at one time within Habitable Zone	- no liquid water currently discovered – life may be extinct on Mars - Mars currently outside Habitable Zone
Europa	+ possibility of warm liquid water below ice crust + heat via tidal forces generated from Jupiter + numerous impact craters from meteors	- radiation that Jupiter exerts on Europa - thick ice crust means life has had to develop independently within Europa (could not be seeded from external sources) - outside habitable zone (although the tidal forces from Jupiter could compensate for this)
Titan	+ organic carbon detected + liquid surface with a methane cycle similar to Earth's water cycle	- outside habitable zone
Comets	+ many million comets in solar system + large random size with differing conditions	- highly elliptical orbit means most comets are frozen for most of their orbit - small size and variability on

		each individual comet
Asteroids	+ Orbit may be in Habitable Zone + Themis 24 contains liquid water	- small mass means lack of atmosphere
Venus	+ atmosphere 45km -70km above surface correct temperature for life + cloud structure at that height cycles between 45km – 70km	- lack of constant source of nutrients for metabolism
Enceladus	+ liquid water + geologically active + no radiation (unlike Jupiter's moons)	- no atmosphere - very small size
Ganymede	+ liquid water	- high radiation from both internal of the moon and Jupiter
Callisto	+ liquid water + low radiation	- cold

Conclusion

As has been discussed in this paper, it is extremely challenging to discover living microbial life remotely, and even more difficult to detect and prove the existence of fossil/extant microbial life. Detailed analysis by humans at the location will be required to confirm definitively the existence of microbial life. While the AHL84001 and Naklha meteorites may have fossil evidence of past life, the sample size is too small, and the results too ambiguous to be a definite proof. It will be easier to find living microbial life in the Solar System. As has been observed on Earth, where there is liquid water, there is life. Therefore, this is where searches should be targeted. The moons of Jupiter are the most logical choice for the likelihood of life existing, with Titan first, followed by Europa. Titan, due to the liquid water found and the organic carbons already detected, and if we did discover life, since it will be in a methane environment, this will be unlike life on Earth and hopefully developed in isolation from Earth. Europa is also a likely candidate, due to the liquid water and heat of the planet.

Although Mars may have had life previously, since there is no evidence of liquid water currently on the planet, proving fossil evidence of simple microbial life is much more difficult. The debate over the AHL84001 and Naklha meteorites is a case in point.

Discovering life on a planetary body, especially that which has developed in parallel to Earth's, will prove that life is common in the universe. Considering the current theory of evolution, that over millennia intelligent life can develop in the right conditions from a single cell organism, it would be safe to assume that we are not alone in the universe.

While no definite evidence of microbial life has yet been found, it is highly likely that it exists in our Solar System, even if it is not a carbon based life form. Judging by how life on Earth has adapted during Earth's lifetime, it is hard to conceive that microbial life does not exist elsewhere. Therefore, the challenge now lies in conducting the research on various planetary bodies in order to discover the evidence of microbial life.

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