Why has life been so successful on this planet, but nowhere else in the universe, to our current knowledge?

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Introduction

Even though, in our galaxy alone, there are around 100 billion planets that spread across a vast universe, we have never found any evidence to support the claim that we are not alone in the cosmos. We have never been contacted or visited by an alien race, we have never stumbled upon extra-terrestrial bacteria when sending probes or men to another celestial body and we have never seen, through telescopes that can scan areas of space 13 billion light years away, evidence of a species, advanced or not, that inhabits a planet that is not the one which we call home.

This concept is, perhaps, one of the most profound yet chilling observations we can make as sentient beings. We have found that the Milky Way contains some 100 billion planets. If just 0.1% of these planets were suitable for life then that would leave 100,000,000 planets that could inhabit life. If, then, 0.1% of these planets went on to, or have already, developed life and 0.1% of those planets developed intelligent life that would still leave 100 planets which were home to intelligent life (of which the human race would be one). Considering, also, that modern humans have only been around for 200,000 years (a cosmic blink of an eye) it is not inconceivable that a proportion of these species would be far more advanced than the human race. Furthermore, the universe is 13.8 billion years old and, using their superior technology, said advanced life forms would have comfortably been able to establish numerous colonies in other star systems, increasing their reach and expanding. Bearing all of this in mind, it is somewhat alarming that we have not encountered even very basic extra-terrestrial life forms; the odds speak for themselves. Such was the belief of the famous physicist, Enrico Fermi.[1] The Fermi paradox is so potent in meaning because it is so simple in principle. Simply put: where is everyone?

Generally speaking, Fermi's paradox leads to one, or both, of two conclusions. The first: due to the scale of the universe these civilisations are simply too far away to communicate with or visit each other. The second: life is immensely more improbable than we had assumed. While it is likely that both are correct, this essay will focus on

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[1] SETI Institute, *Fermi Paradox* http://www.seti.org/seti-institute/project/details/fermi-paradox (accessed 23 July 2016)

the latter and will attempt to determine what makes this planet, and the life on it, so unique.

Entropy

In order to understand how life came to be we must first understand how the simplest of biological molecules were synthesised from nothing but elements. Spontaneously creating order from chaos is a physical impossibility. This concept is known as the second law of thermodynamics and it states that the level of disorder (entropy) in any system must increase over time. However, the very existence of life seems to go against this fundamental concept: how can it be that complex molecules and life forms have come to exist, seemingly spontaneously, from nothing but elements? The answer lies in the fact that entropy is broken down into two sub-categories: entropy of the system and entropy of the surroundings. This is summarised in the following expression:

$$S_{universe} = S_{surroundings} + S_{system}$$

What this implies is that is it possible for a group of molecules with high entropy to group together and become ordered, provided that the surroundings becomes more disordered than the molecules have become ordered. In fact, this is precisely what happens in biological reactions. The vast majority of these reactions are highly exothermic, meaning that, although the entropy of the molecules involved in the reaction has increased, they have released a considerable amount of energy to the surrounding molecules, providing them with kinetic energy, making their movement more random and thus causing their entropy to increase. For example, one of the most fundamental and ancient reactions, respiration, is able to produce energy in the form of ATP from oxygen and glucose, two very simple molecules in comparison. It is able to do this because it is highly exothermic and heats up the surrounding molecules, causing them to become very disordered. As a result, this reaction is entropically favourable.

Thermodynamics is the driving force of all organisms on this planet. If molecules do not want to react, they will not. Luckily, the Earth is an ideal environment that gives molecules that would normally never react the chance to form compounds and, eventually, create life.

Fundamentals

Entropy is a somewhat abstract concept; the next pillar that supports life is the opposite. There are two necessary conditions that a planet needs to meet for it to be able to support life. Firstly, it must be temperate. This is because biological reactions are very sensitive to temperature change and so they can only occur within certain ranges. Furthermore, the planet must be accommodating for water, which is one of the most important components for the birth of life. Secondly, the planet must have a stable and thick enough atmosphere in order to provide organisms with vital gases but also to shield the planet from harmful cosmic rays.

Essentially, a planet is said to be in the 'Goldilocks' Zone' of the star if its climate is temperate enough for water to exist in the liquid state. As will be explained later, water is thought to be the most important prerequisite for the existence of life; without it even the simplest life forms cannot form. Fortunately, Earth sits in the Goldilocks' Zone of our star and this is one of the most important reasons why life has been so successful here. The highest ever-recorded temperature on Earth is 58°C and the lowest is negative 88°C, giving it a temperature range of 146°C.[2] This range is not dissimilar to that of our cosmic neighbour, Mars, which varies from negative 133°C to 27°C, giving a range of 160°C. However, the average temperature on Mars is an unaccommodating negative 55°C[3], thus making it unable to support liquid water and, therefore, life. On the other hand, Earth has an average temperature of 15°C[4], which is hospitable to water. The fact that one of these harbours 8.7 million species[5] while the other 0 tells us that it is not the temperature range of the planet that is important but where the average temperature lies. Therefore, it is clear that if a planet ever hopes to support life it must be in the Goldilocks' Zone of the star it orbits and also must have liquid on the surface.

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[2] Cool Cosmos, *What are the highest and lowest temperatures on Earth?*
http://coolcosmos.ipac.caltech.edu/ask/63-What-are-the-highest-and-lowest-temperatures-on-Earth- (accessed 26 July 2016)
[3] Nine Planets, *Mars Facts*
http://nineplanets.org/mars.html (accessed 26 July 2016)
[4] Universe today, *What is surface temperature of the Earth?* (2016)
http://www.universetoday.com/14516/temperature-of-earth/ (accessed 26 July 2016)
[5] Science daily, *How many species on Earth?* (2011)
https://www.sciencedaily.com/releases/2011/08/110823180459.htm (accessed 26 July 2016)

The second requirement that a planet needs to meet is related to its atmosphere. An atmosphere is of paramount importance to both complex and simple life forms and its use is two-pronged. Firstly, it provides all organisms with vital gases that we could not survive without. As large, respiring mammals we take in immense volumes of oxygen each day just so that we can continue existing; a planet needs an atmosphere to support terrestrial life. Earth is lucky enough to have an atmosphere of the correct thickness and it has a sufficient gravitational pull that ensures that our atmosphere does not escape into space. Other planets are not so gifted. Although Mars is just over half (53%) the size of Earth, its mass is some 10 times less than that of Earth. As a result, the force of gravity on mars is 38% that of Earth and this makes it unable to maintain a thick atmosphere.[6] Furthermore, while an atmosphere is important, having an atmosphere that is too thick and violent is as detrimental as having no atmosphere at all. Take Venus, for example. It is our closest neighbour in the opposite direction to Mars and has a mass equivalent to 80% that of the Earth. However, its atmosphere is around 90 times thicker than Earth's. The result of this is a greenhouse effect on a massive scale that causes surface temperatures of 462°C and pressure that could kill instantly; standing on the surface of Venus you would experience a pressure equivalent to diving to a depth of 3,000 feet below sea level.[7] Naturally, this is not desirable for life in every way and is the main reason that Venus is a barren world.

Secondly, the use of an atmosphere is not only to provide organisms with important gases but also to shield them from harmful cosmic rays. On Earth we are protected from the sun's harmful ultraviolet light by a thin layer in our upper atmosphere called the ozone layer. This is necessary for the survival of life on Earth as it would be quite difficult for us to survive if we were constantly bombarded by these rays. This is why it is so unlikely for there to be terrestrial life on a planet with no atmosphere and, therefore, no protection. We can, therefore, conclude that an atmosphere is essential for the formation of life as it protects it and nurtures it. Our atmosphere is one of the components of our planet that makes it unique in the solar system and possibly in the whole universe.

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[6] Space.com, *How big is Mars? | Size of planet Mars* (2012) http://www.space.com/16871-how-big-is-mars.html (accessed 27 July 2016)
[7] Space.com, *How hot is Venus?* (2012) http://www.space.com/18526-venus-temperature.html (accessed 27 July 2016)

The Young Earth

Now that we have discussed generally the prerequisites for life to form we can examine how life could have formed on Earth - the only environment that has been successful so far. One theory of how the first biological molecules came to be was from a 'primordial soup', which was made up of the components of the most basic organic molecules. The theory states that at some point when the Earth was young there was a warm body of water that contained molecules such as methane, ammonia and hydrogen. This body of water was, at some point, struck by lightning, providing the necessary activation energy for these molecules to coalesce into organic molecules.

During the mid 20th century two biochemists, Stanley Miller and Harold Urey, attempted to recreate the conditions that were present on the young Earth and, using some basic molecules that they thought were abundant at the time and a spark to simulate the lightning, synthesise basic biological molecules. In a container they placed gases such as ammonia, hydrogen and methane coupled with water in the form of vapour. Electrical sparks were then passed through this mixture in order to mimic lightning and provide activation energy. The pair then returned to their apparatus after several months with the hope of finding some basic organic molecules. What they found was beyond encouraging. [8]

Upon returning they found not only numerous organic molecules but also some amino acids, which could go on to form proteins eventually. Their experiment had seemed to give conclusive proof as to how life on Earth began. However, they were, unfortunately, going down the wrong path from the very beginning. They had certainly shown that organic and biological molecules *could* be synthesised from these basic gases, but closer examination of rock formations showed that the gases that Miller and Urey used for the experiment were not abundant on the young Earth. The gases that were present, however, were carbon dioxide, nitrogen and traces of methane. When the same experiment is repeated with this combination the yield of organic molecules is unsatisfyingly low. Furthermore, none of the molecules within

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[8] N. Lane, *Life Ascending* (London: Profile 2010) p.11

the primordial particularly 'want' to react. That is to say, linking back to what was discussed earlier, that their reacting is not entropically favourable and they will not do so easily. The 'primordial soup' argument is one of the most popular theories of how life began. It could be argued that this is because it is so neat and convenient; it seems to be logically sound. As humans we crave patterns and logical explanation. However, in nature these things are scarce and when they are found they quickly become in need of restructuring due to anomalies and exceptions. Bearing in mind the facts and the unsettling elegance of the primordial soup model, it is clear that we need to find a more suitable explanation for how life began on Earth.

One such explanation could be found from the reaction between hydrogen and carbon dioxide. The chemical equation for the Sabatier reaction, as it is called, is as follows:

$$\mathbf{CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O + energy}$$ [9]

As we can see this reaction produces methane, an organic molecule, and energy, from only hydrogen and carbon dioxide, two molecules that were abundant all those years ago. This reaction requires activation energy and a nickel catalyst in order to run to completion. Luckily, this nickel catalyst is in abundance around hydrothermal vents at the bottom of the ocean. Furthermore, the heat from these vents is able to provide the necessary activation energy for this reaction.

The warm water around these vents is rich in dissolved gases such as carbon dioxide, ammonia, hydrogen sulfide, hydrogen cyanide and carbon monoxide. This mixture is a breeding ground for organic molecules and, when supported by numerous metal catalysts in suspension around these vents, the yield is high. Once these organic molecules have formed, they can then react again with another catalyst in order to produce more complex and larger molecules in what is, essentially, a chain reaction.

We have seen, therefore, how organic molecules can be easily synthesized, but how can these molecules coalesce to form complex biological molecules? A man called

[9] Pennenergy.com, *The Sabatier Reaction, Possible Solution to CO2 Emissions* (2010) http://www.pennenergy.com/articles/pennenergy/2010/03/the-sabatier-reaction.html (accessed 24th July 2016)

Günter Wächtershäuser suggested an explanation. The evolutionary biochemist devised a theory, which he boldly named the 'Iron-Sulfur World Theory', which suggested that, after basic organic molecules were synthesized, what was required was a simple metabolism that would convert these simple molecules into larger and more complex ones.[10] The issue with metabolism in the primordial era was the lack of oxygen. Today nearly all living cells use respiration as their pathway to obtaining useful energy. However, respiration is a complicated process that involves glucose, an organic molecule too large and complex to be available in abundance when the Earth was young, and oxygen, which was also not available. Currently, bacteria that live in proximity to hydrothermal vents use the reaction between hydrogen sulfide and oxygen in order to release energy. Again, there was very little oxygen present on Earth and so the earliest life forms could not have used this method. This is where Wächtershäuser's 'Iron-Sulfur World' comes in. He suggested that the reaction of hydrogen sulfide with iron to form iron pyrites and useful energy could have been used as a form of metabolism for the first life forms.[11]

Although this theory seems the most sound, there are still some issues with it. The most prominent of which applies to all of these theories. It is that these molecules, which are reacting and attempting to form highly complex structures such as proteins and DNA, are dissolved in large bodies of water, in the second case entire oceans. Due to this fact the immediate issues are that, firstly, the reactions are not contained and, secondly, due to the lack of containment the number of particle collisions would be extremely low. This does not bode well for the formation of said complex structures, as nowadays they need to be carefully monitored in a controlled environment: the cell.

Although we have encountered some issues with these models, we can see that this planet was lucky to be rich with building blocks of basic organic and biological molecules. We have seen that the aid of hydrothermal vents on the ocean floor could have provided the perfect breeding ground for these molecules and that, essentially, the Earth was well catered for life from the very beginning.

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[10] Space.com, *Earth May Have Originated at Deep-Sea vents (2013)* http://www.space.com/19439-origin-life-earth-hydrothermal-vents.html (accessed 24 July 2016)

[11] Lane, p.16-17

Oxygen and Water

Oxygen and water are the two most vital molecules to all organisms on this planet; understanding their importance will tell us more about why life cannot exist without them. An important question to ask is why do we breathe oxygen when it only makes up 21% of the air around us? The answer is that oxygen is much more useful than nitrogen, for example, which makes up 78% of the air we breathe. In fact, it is not so much that oxygen is 'useful', more that it is reactive and so can easily take part in reactions whilst nitrogen cannot. Oxygen is the second most electronegative element, which makes it a fierce oxidising agent. This becomes important when it reacts with carbohydrates, such as glucose.

Producing ATP in the body is a complicated process, involving many steps. From one glucose molecule around 30 molecules of ATP can be synthesized through this process. Approximately 87% of these molecules are synthesized in the very last step. This last step is what provides the energy that can then be converted into 26 ATP molecules and it is where oxygen becomes important. Nicotinamide adenine dinucleotide (NADH) and flavin adenine dinucleotide ($FADH_2$) are the reduced forms of the electron carriers NAD^+ and FAD and are produced in the following reactions:[12]

$NAD^+ + 2e^- + 2H^+ \rightarrow NADH + H^+$

$FAD + 2e^- + 2H^+ \rightarrow FADH_2$

Oxidative phosphorylation then occurs. The pairs of electrons gained by both molecules have a high electron transfer potential and so will move easily in the presence of an electrophile, in this case oxygen. The electrons are accepted by oxygen, reducing it to water and carbon dioxide and releasing free energy in the process. This free energy is then used to produce ATP.[13]

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[12] Khan Academy, *Steps of Cellular Respiration* https://www.khanacademy.org/science/biology/cellular-respiration-and-fermentation/overview-of-cellular-respiration-steps/a/steps-of-cellular-respiration (accessed 28 July 2016)

[13] *Biochemistry. 5th Edition*, Chapter 18 – Oxidative Phosphorylation (New York: WH Freeman 2002) pp. 739-740

Therefore, we can see that oxygen is vital to all living things on Earth for two reasons. Firstly, it is a reactive oxidising agent and so easily oxidises NADH and $FADH_2$ to produce ATP in cellular respiration. Secondly, it is readily available to us by being in the air we breathe. Oxygen is a reactive and useful molecule that is easily obtainable and so it is no surprise that it was chosen as the basis for metabolism in our ancestors and why it is now an irreplaceable asset to all organisms.

Water is somewhat the more important molecule of the two. There was life on Earth before there was oxygen; we can gather that water is higher up in the rankings of vital value. In fact, we believe water to be so important that life cannot develop on any planet without it. Water is so versatile and useful because it boasts several useful properties that allow it to catalyse the formation of life forms.

Firstly, water is a polar molecule. Due to oxygen being far more electronegative than hydrogen, it pulls the electrons in each covalent bond closer to it, meaning that close to the oxygen there is a higher density of negative charge than close to the hydrogen atoms. Because of the bent shape of the molecule, these dipole moments do not cancel out and the molecule is left with a permanent dipole moment.

Being a polar molecule, water is an excellent solvent as it can form intermolecular bonds with the solute easily. Therefore, the building blocks of life are able to dissolve in water and be carried around more easily than they would normally. In turn, this increases the number of collisions between these molecules by allowing them to mix, allowing organic and biological molecules to be synthesized with a greater yield. As a result of this, it makes it easy for solute to be transported across cell membranes because the dissolved material can simply flow into the cell via water.[14]

These two molecules are of utmost importance to life. While there are some organisms that do not use oxygen, there are none that do not make use of water and this is what makes Earth so lucky: we were blessed with this vital medium that allowed the first life forms to exist.

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[14] Live Science, Why is water so essential for life? (2015) http://www.livescience.com/52332-why-is-water-needed-for-life.html (accessed 29 July 2016)

Alternatives?

Although water and oxygen are needed for life, are there any other molecules that alien life forms could be using as alternatives? Surely similar molecules could serve the same purposes as oxygen and water while having different compositions? The answer is that there are substitutes for both but none of them are as desirable as oxygen and water.

A good place to start would be the other abundant gases in our atmosphere. None are ideal, unfortunately. N_2, the most abundant of the gases, is almost completely inert due to the robust triple bond between the two atoms. Carbohydrates such as glucose need to be oxidised in order to release energy and generate ATP, oxygen is a good oxidising agent, and this is why it is such an ideal molecule. However, chlorine is a better oxidising agent than even oxygen and so why has nature chosen oxygen over chlorine? The use of chlorine as an oxidising agent comes with detrimental costs; namely, in contact with water it forms hydrochloric acid. This lowers the pH of the solution of organic molecules and ruins the chemistry between them; reactions become impossible and biological molecules cannot be synthesized.

Water is so useful to life because it is an excellent solvent. There are, however, a great number of excellent solvents, yet water is the one that nature chose. This is because the range of temperature in which it is liquid covers the optimum temperatures of most biological reactions. Ammonia, for example, another polar molecule, is also an exceptional solvent. The issue with ammonia is that it forms very weak intermolecular forces with other ammonia molecules and, as a result, is liquid at extremely cold temperatures. Since biological molecules cannot form stably at these extreme temperatures, ammonia is useless and water comes up trumps.

We can therefore see that there are viable substitutes for both of these molecules. However, nature tends to discard anything that causes difficulty in favour of a simpler solution; water and oxygen are that solution. They are the most accommodating and useful of these molecules, and that is why we still use them eons after the dawn of life.

Conclusion

It is difficult to pin the success of life on Earth on just one of the elements mentioned above. Rather, it is the combination of all of these entities that has allowed life to be successful. Why do we live on such a unique world? Simply put, it is all down to luck. The Earth was lucky enough not to be too far away from our star, but not too close either, lucky enough to be massive enough to hold onto our atmosphere, lucky enough to have oceans of water. Just by existing we have beaten odds of astronomical proportions and we are yet to find another planet in the universe that is as well suited to life as this one. There is no doubt that the biology of the organisms that would live on such a planet would astound us, but until that day we must continue searching and be thankful for our inconceivable good fortune.

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