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A review on the spontaneous formation of the building blocks of life and the generation of a set of hypotheses governing universal abiogenesis

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Abstract: There have been a number of hypotheses regarding abiogenesis, the 'Metabolism First' model and the 'RNA World Hypothesis' are two such examples. All theories on abiogenesis make a set of unstated assumptions with regard to the elemental make up of life or only apply the theory to a primitive earth model. This paper reviews current knowledge from the myriad of observations from a variety of scientific disciplines and applies generally understood thermodynamic reasoning to explain the formation of molecules known to be used by life. These arguments are used in this paper to construct a set of new hypotheses which govern universal abiogenesis. The intention of this paper is to show by the application of our known laws of science that life is the end sequence of events of the fundamental forces which affect the entire universe. From these events a new hypotheses on abiogenesis can be formulated. The hypotheses proposed by this paper are incorporated in many of the current theories of abiogenesis, either assumed or accepted but very rarely stated or explained. The proposed set of five hypotheses are: (1) any celestial mass that has a body of liquid water and therefore has access to energy will form at least the building blocks of life, if not life itself. (2) The major component of any life form anywhere in the universe will be H_2O. (3) Any organism, anywhere in the universe, will be carbon-based. (4) All life in the universe will be composed of nucleic acid based molecules as its code for life. (5) The cell is the universal unit of life. Throughout this paper the background to the formulation of these hypotheses is discussed, as is the explanation of why these hypotheses are universal and not limited to an application of a primitive earth model. This set of hypotheses is also testable as any investigation of a celestial body which contains liquid water (e.g. Europa) will quickly provide evidence to prove or refute the proposed theory.

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Introduction

A review of universal biochemistry has been performed before (Pace, 2001; Chela-Flores, 2007), but in order to formulate a set of universal hypotheses, an understanding of what is widely accepted has been summarized first. The cosmological principle states that 'on large spatial scales, the universe is homogeneous and isotropic'. The present size of our observable universe is 93×10^9 light years in diameter (Cornish *et al.* 2004) and spectroscopic analysis of the light from distant stars and galaxies can inform us of the atomic and molecular make up of these distant objects. The results demonstrate that the light, and hence atoms, are the same in these stars and galaxies as here on earth. If the electromagnetic spectrum is the same throughout the universe, it may be observed that the remaining fundamental forces of nature: the weak nuclear force, the strong nuclear force and gravity must also be the same. Therefore, all of matter in the universe and its physical and chemical behaviour are also the same.

The birth of atoms, stars and simple molecules

The nuclei of the light elements of H, He, ^{2}H and Li were born from The Big Bang Nucleosynthesis (Coc *et al.* 2004). Over the next one Ma the universe cooled and through recombination, the ions of H and He gained their electrons and became atoms as we know them today. The gas that remained was spread throughout the universe as a mixture of H (75%) and He (25%) (Thuan & Izotov, 2002). A Ga after the big bang the first galaxies started to coalesce throughout the universe (Springel *et al.* 2005) and within these small galaxies the first stars were born (Yoshida *et al.* 2006).

After the first stars had burnt the majority of their hydrogen fuel, and had formed the key elements of C, O, N, extending through the periodic table up to and including Ni and Fe (NASA, 2011), they exploded into the most violent of natural phenomenon known in our universe, the supernovae (Ellis & Schramm 1995; Iwamoto *et al.* 2005; Woosley & Janka, 2005). The force of these explosions spread the remaining debris throughout the local area of the former star producing a nebula (Modjaz, 2007; Smith *et al.* 2007), ly's across, that contains many kinds of simple molecules made up of different combinations of elements (Zeilik, 1997). Any element, when released in a supernova explosion, will more than likely encounter H_2, as this is the main constituent of a star. Any unstable molecules will eventually disintegrate or react with one another to form a more stable configuration.

Stars that have gone supernova have their remains contributing to the interstellar medium (ISM). ISM constitutes 99% gas and 1% dust. The gas itself is made up of approximately 90% H, 8% He and 2% of other elements (Hudson, 2001). The shock wave from the exploding star and other explosions throughout the galaxy help to seed new stars (Roberts, 1969) from the remaining nebula. The debris and gas from the nebula will eventually collapse with small particles clumping together, which will gradually enlarge (Dullemond & Dominik, 2005). A secretion disc will ultimately organize itself around an ever growing protostar (O'Dell & Wen, 1994). As the secretion disc continues to collapse under gravity this potential energy is transformed into kinetic energy as it gains rotational speed. Particles of H_2O and other light molecules will vaporize and be transported to areas away from the centre, while heavier elements, e.g. iron, will condense nearer to the centre of this newly forming solar system (Ciesla & Cuzzi, 2005). Eventually the protostar will ignite and a star and its new system will be born. Ultimately after the process has repeated often enough, there is sufficient of the heavier elements present for rocky planets to form around another generation of new stars (Holland *et al.* 1998).

Atoms, simple molecules and the birth of stars and their systems are nothing more than a consequence of the laws of physics. Our planet is one of eight and is not an exception to the rule as planet formation is a common process with planets of differing sizes being discovered around many star systems (Borucki *et al.* 2003; Marois *et al.* 2008).

Water: where, why and how?

H_2O is universally abundant, why? Why not any other hydrogen compound, e.g. H_2S, H_2N, CH_4 or SiH_4? The reason is quite simple. The standard Gibbs energy of formation is much more favourable for H_2O ($\Delta_f G° = -237.1\ \text{kJ mol}^{-1}$) then for any other hydrogen compound (e.g. $\Delta_f G°$ for $H_2S = -33.6$, $H_2N = -16.5$, $CH_4 = -50.7$ and for $SiH_4 = +56.9\ \text{kJ mol}^{-1}$) (Shriver *et al.* 1994). Also the average bond enthalpies are considerably higher for H_2O than for any other hydrogen compound, bar HF and as oxygen is much more abundant than fluorine, then it comes apparent why H_2O is so plentiful throughout the universe.

H_2O is one of the most important, and universally abundant molecules throughout the universe (Sandford & Allamandola, 1993), with a wide range of physical and chemical properties that are unique to H_2O and are mainly due to the regular tetrahedron shape of the electron hybrid orbitals of H_2O (Shriver *et al.* 1994).

H_2O demonstrates the effects of shielding and de-shielding, giving H_2O its polar properties and allowing the phenomenon of hydrogen bonding. Hydrogen bonding is not exclusively a property of H_2O as it is present in many hydrogen-containing molecules, e.g. ammonia, alcohol, hydrogen fluoride, DNA and many others; but due to the bend in H_2O the effect of the hydrogen bond is amplified. This bond, although weaker than a conventional bond between atoms, still has the strength to greatly increase the melting and boiling points of the substances concerned by hundreds of degrees when compared with similar molecular weighted molecules where there is no or minimal hydrogen bonding (e.g. methane, mp −182.5 °C and a bp −161.6 °C). Hydrogen bonding also gives H_2O another important property; as a solid it is less dense than its liquid state and as ice is a poor conductor of heat. Floating ice helps insulate the lower liquid component of water helping it to stay liquid.

For H_2O to be a liquid it is a simple matter of having the required amount of energy. On Earth we get the energy we require from two sources, the Sun and the Earth's active interior. In other areas of the solar system, gravitational tidal energy imparts energy into a planetary body, e.g. Europa, allowing for an active core (Squyres *et al.* 1983; Carr *et al.* 1997) and a layer of liquid water under Europa's ice caps.

H_2O is also considered to be the universal solvent due to its shape and inherent polarity. As differing molecules react they form an unstable intermediary, which can break down back into its previous state. H_2O is able to stabilize these intermediaries so the probability of a successful reaction is greatly increased as a greater period of time is allowed to pass for the full reaction to take place (Maskill, 1996). This ability to stabilize does not occur with oils or any other hydrocarbon, but can occur with other types of polar molecules, e.g. acids or alcohols. This capacity to stabilize has a direct effect on the rate of reaction as H_2O can increase the rate of reactivity by 1×10^5 times when compared with ethanol (McMurry, 1996).

Due to the small size and polar nature of the H_2O molecule, it is able to cover small particles, enabling them to dissolve, assisting them to adhere to each other and bringing them together. The bringing together of particles does not necessarily happen in a random manner. This has been revealed by experiments where virus particles have been dismantled into their smaller units. These separate units are then placed into water and the virus is able to self-assemble back into its original form (Ceres & Zlotnick, 2002; Chen *et al.* 2008).

These many properties are fundamental to H_2O, which makes water not just vital to life but essential for life's existence. It may still be argued that other liquids could take this role and H_2O is not so essential. This does not take into account a key property which is not seen in any other fluid: H_2O cannot be burnt. H_2O cannot be oxidized any further making H_2O extremely stable, as demonstrated above by the standard Gibbs energy of formation as well as the average bond enthalpies of H_2O, which is another reason why H_2O is so abundant throughout our universe.

H_2O, due to its physical and chemical properties, is profoundly important not just for life on earth but for the existence of life anywhere in the universe. Without H_2O complex life could not exist, in fact without H_2O life would not even be triggered in its simplest form. Even if life did form, without H_2O it would quickly be reacted back to its simple building blocks as H_2O is needed to stabilize complex molecules and to allow complex molecules to react and evolve.

When we review all of the properties of H_2O, we can formulate the first hypothesis of universal abiogenesis:

> *Any celestial mass that has a body of liquid water and therefore has access to energy, will form at least the building blocks of life, if not life itself.*

Life started from the most simple of building blocks with the interaction of H_2O. This allowed for molecules to be stabilized and for controlled reactions to take place. As H_2O is the most stable and one of the most abundant molecules in the universe, we can immediately conclude the make up of life with the second hypothesis:

> *The major component of any life form anywhere in the universe will be* H_2O.

The element of life

The largest proportion of elements in the periodic table are metals. Metals by their nature cannot be the basis of life, quite simply because they are usually oxidized down to their most stable compound. The very few metals that do not react with H_2O, e.g. gold, will also not form life, as life needs molecules that are stable, but will undergo reactions. A reactionless element in this context could not become a basic life-forming molecule. This argument then also takes out the group eight elements, the noble gases, because of their near absolute lack of reactivity.

The group seven elements, 'the halogens', can be found within carbon molecules, but due to their reactivity they can never form long halogen chains. Any bond between any of the halogens is highly unstable when in the presence of other elements or molecules.

This leaves the elements of C, Si, O, N, S, P and Se. The position of O, S and Se as group six elements immediately dictates that their chemical versatility is reduced due to the presence of an antibonding orbital, thereby cutting the bonding potential. Oxygen has a high electronegativity when compared with carbon so has a smaller covalent radii and therefore generally forms stronger bonds. All the group six elements that are heavier than oxygen usually form single-bonded molecules, not only will this limit their bonding capacity it will also mean that a single-bonded group six element will have to bond to another element in order to stabilize its outer shell. This usually results in large chains being formed and, as a consequence, these elements are nearly always found as solids in their natural state as opposed to a gas or a liquid. Sulphur is found on earth as a crystalline solid and in nature, commonly forms octatomic molecules thereby limiting its capacity to be the bases of life. The remaining group six elements also have the ability to form rings and this enables them to form stable crystalline structures, they also become increasingly rare as you descend the group. The last two elements to be discussed are in group five: N and P. Both elements are highly important for life, but life itself is not based on them. N_2 is a triple-bonded molecule, is very stable and too unreactive to form the basis of life, also many of the nitrogen hydrides and oxides have a positive Gibbs energy of formation which reduces the versatility of nitrogen.

Phosphorus is found wherever life is found and is the backbone of DNA and RNA, it is also found in lipid bilayers. Although phosphorus is a key element and without it, life as it is known would not exist, it must be remembered that phosphorus, unlike carbon, is not found in every molecule, but is found in some very important structural components and can sometimes be replaced by other elements, e.g. arsenic (Wolfe-Simon *et al.* 2011). Phosphorus cannot be the basis of life because phosphorus has a much larger covalent and ionic radius when compared with carbon (covalent radius of 1.10 Å for P; 0.77 Å for C) this longer radius means longer, weaker bonds, reduced bonding enthalpies and thus more instability. Phosphorus is also highly reactive and is never found as a free element, in its natural state phosphorus tends to be a polymorphic solid and in life needs to be backed up by a more complex carbon structure in order to support it. Phosphates, one of the most important phosphorus-based compounds for life, also have generally low solubility. Without a stabilizing carbon structure, phosphorus, due to being highly reactive, would quickly react back down into its natural state as a stable mineral.

It has been suggested that silicon could be the element in which life might be based (Lazio, 2011), as silicon is found in the cell walls of diatoms as a major structural component (Reimann *et al.* 1965). Silicon also has the ability to form long chains due to its position in the periodic table, group 4, and has similar chemistry to carbon. Silicon, however, is a metalloid, is the second most common element found in the Earth's crust, after oxygen. This commonality gives us an indication as to why it cannot be the basis of life. Firstly silicon is just not as versatile, once it has reacted with oxygen then it effectively becomes an inert material due to the favourable changes in enthalpy and Gibbs free energy change for SiO_2 ($SiO_2(s)$ $\Delta_f H° = -910.94$, $\Delta_f G° = -856.64$; compared with $CO_2(g)$ $\Delta_f H° = -393.51$, $\Delta_f G° = -394.36/\text{kJ mol}^{-1}$) (Atkins, 1998). Most of silicon's chemistry is based on its reactions with oxygen. SiO_2 is an unreactive solid, most often seen as sand, unlike CO_2. CO_2 is a very stable molecule, but due to its linear shape and that it is a gas at room temperature and pressure means that CO_2 is more versatile and given the right conditions can be readily reacted with. Silicon tends not to form ring or chain structures unless the chains include oxygen in every other atom but this is, or will become SiO_2. All the metalloids have the problem of low chemical versatility, such as silicon, so cannot be the element of life.

Carbon is common and is found throughout the universe. Carbon is the fourth most abundant element in today's universe, behind H, He and O (Blair & Raymond, 1984). All the allotropes of carbon (graphite, diamond and fullerenes) are incredibly stable. Unlike every other element, carbon is the most versatile. It is the only element that has the ability to form chains, rings and multiple bonds not just with itself but also incorporating other elements into its molecules. No other element has this flexibility. Every organism on this planet is made up of carbon-based molecules, other elements such as O, N, S, P, etc., are included into carbon-based molecules, but these are usually just one or two atoms in a larger carbon structure.

Carbon is a unique element with a set chemistry and can form many different types of molecules. However, the types of molecules carbon can form are not random nor organized, but are the end result of the most likely probability given what other elements it can react with and which of those molecules are the most stable.

Carbon-based molecules can be formed in some of the most hostile environments. The most hostile of which is space, where many small molecules are formed (Watson et al. 2004). There has been a great deal of research into the analysis of nebulas and the examination of the light from them which has shown to contain many small molecules, e.g. carbon monoxide through to formaldehyde (CH_2O) (Evans *et al.* 1975).

Larger organic molecules have also been discovered in interstellar space, most notably formamide (NH_2CHO), and the larger molecule acetamide (CH_3CONH_2) (Hollis *et al.* 2006). Acetamide ($CH_3CO–NH_2$) contains an amide bond, an important discovery in interstellar space, as it shows that many types of common chemical bonds arise across the universe. These molecules have been selected for and hence are more likely to survive than others. The existence of the amide and other chemical bonds is not just chance events, these bonds exist as they have the most stable configuration than the corresponding enol tautomers or when compared with their Si, S and P analogues (Chiaramello *et al.* 2005).

Larger carbon-based molecules have also been found in space containing not only single-ringed structures but different combinations of joined rings (Geballe *et al.* 1989). Nitrogen containing carbon aromatic molecules have also been discovered in the depths of space (Peeters *et al.* 2005), but nitrogen containing aromatic molecules are unstable in UV light, yet provided they are found in a sheltered place away from UV light, such as within a nebula, then they can still be found in space. Taking everything that has been discussed, carbon is the only element suitable for life, as it is the only element with a favourable chemistry. We can therefore conclude that as carbon is found throughout the universe and is subject to the same laws of physics as in our solar system then we can now formulate the third universal hypothesis of life:

> *Any organism, anywhere in the universe, will be carbon-based.*

Other types of carbon and nitrogen compounds have been synthesized by NASA in simulated space environments, such as the pyrimidine molecule, uracil (Marlaire, 2009), found in RNA.

The other bases in DNA are adenine and guanine both of which are purines. However, there are hundreds of different types of purine molecules, e.g. caffeine and uric acid to name but a few. So why are only adenine and guanine found in DNA, why not hypoxanthine, uric acid or caffeine? This is because other types of purine would either not stabilize the DNA molecule enough or instead, stabilize and bond too strongly to its pyrimidine partner. Most hydrogen bond (····) energies in DNA are (N–H····O or N–H····N) 8–13 kJ mol^{-1} of energy. However, bonds with other purines, when the nitrogen has been replaced by an oxygen atom (O–H····O or O–H····N) have a range of energy values of 21–29 kJ mol^{-1}. Another argument is that the other purines would suffer an atomic repulsive interaction of steric strain. So by a process of chemical evolution adenine and guanine are the only self-selected acceptable purines.

What we have seen is that nature favours certain molecules over others; this is because some molecules are more chemically stable, due to a more favourable Gibbs free-energy change and enthalpy change. These stable molecules are more likely to stay in their local environment longer than others (Kwok, 2009). In evolution you can only evolve from what is already present. Molecules behave in a similar fashion as they can only evolve by reacting with what is in their environment.

An experiment that demonstrated that organic molecules, such as amino acids are a natural consequence of the environment, was performed by the chemists Stanley Miller and Harold Urey in 1952. Sugars, lipids and other organic molecules were also formed when the experiment was repeated by other scientists. A total of at least 22 amino acids were reported to have been formed (Johnson *et al.* 2008).

There were many variations of how the chemistry of life could have come together, but for chemical stability and reliability the molecules we have now are the ones which were selected for 3.5 and 4 Ga ago. This natural chemical selection would happen everywhere in the universe where there is liquid H_2O. As amino acids and the nucleic bases are a natural consequence of chemical evolution, we can formulate the forth hypothesis of life:

> *All life in the universe will be composed of nucleic acid based molecules as its code for life.*

Amphiphiles and phospholipid bilayers

Amphiphiles, commonly called lipids, are extremely important and common substances. Amphiphiles are simple structures made of a hydrophobic carbon chain and a negatively charged hydrophilic phosphate structure (McMurry, 1996). As large phospholipid structures were probably formed as soon as liquid water was present on the Earth's surface, then various lipid structures are likely to have been formed quickly. The predictable physical properties of phospholipids dictate all of their behaviour. When a small amount of phospholipid is placed in water and passed the Critical Micelle Concentration (C.M.C.), the phospholipids will naturally aggregate mainly due to the properties of water (see above).

The structures formed are dictated by the difference in the cross-sectional area of the head compared with the tail. If the head of the lipid is much larger than the tail then a micelle structure is formed. If the head is only slightly larger than the tail, then rod/cylinder like structures are formed (elongation of the micelle structure). And lastly if the head and tail are of a similar size then they will form a bilayer (Hamley, 2000).

The majority of phospholipids chains are between 12 and 20 carbon atoms long (McMurry, 1996). However, in living cells only one or two lengths are usually found and this is commonly connected to a biological function. With regard to concentration needed to form a phospholipid structure, a high concentration is required to form micelles with a low number of carbons in their chains. But the C.M.C. varies with chain length, the longer the chain then the lower the concentration of phospholipid. For every carbon atom added decreases the C.M.C. needed by a factor of 2–3 for that particular length of phospholipid. This relationship with length continues up to a carbon chain of approximately 16 carbon atoms (the median of the number of carbon chains found in living cells) (Hamley, 2000). The formation of micelles is driven by two factors the first is a favourable entropic effect due to local restructuring of H_2O molecules into a loose tetrahedral arrangement; the second is a favourable enthalpic interaction between the hydrocarbon chains (Hamley, 2000).

There is a great deal of self-selection as the concentration needed to form any structure is lower for single chains than those with branches in them (Hamley, 2000). Another factor that decreases the C.M.C. is when salt is present in the water. Salt, an ionic chemical, allows the phosphate heads to come closer together by reducing the repulsive charges. This effect is greater for long-chain molecules than short chains (Hamley, 2000). This then sets the scene as phospholipid molecules that are too short do not form anything as their concentration is too low, but they then continue to react until the chains become longer. If the chains become branched then this too is selected against, due to the physical disadvantage branched phospholipids have inherent in their structure. Only when single-chained lipids come to a set length will they have the correct concentration in order to form the structures described above.

On a primitive Earth-like planet with liquid water, a mix of different organic chemicals, phospholipids of various kinds, sugars, nucleic bases and many different types of amino acids were formed. Some of the chemicals may have even formed in the solar system or beyond before the sun even ignited and accumulated on a frozen earth via a comet (Rauf *et al.* 2010; Kwok, 2009) to await the Sun's ignition. Many of the present day theories regarding the origins of life assume that life had to have a single point from which to start and they appear to argue between themselves that one of the molecules named above had to be formed first and the others forming around it. This appears to be incorrect as everything we have discussed so far happens spontaneously and independently, provided the basic conditions (e.g. presence of liquid water) have been met.

Nucleic acids and the RNA world

On the primordial Earth nucleic acids of any type are formed spontaneously. The question that arises is how did the first nucleotides come about? Mononucleotides or dinucleotides are unable to form stable hydrogen-bonded structures in H_2O, but are able to form and transmit genetic information within a protein cage (Tomohisa *et al.* 2009) or within the hydrophobic cavity within a micelle. With nucleotide structures and other organic molecules trapped within a phospholipid structure, a protobiont, can be formed spontaneously.

It has been previously shown that RNA may have also formed spontaneously within the primordial soup (Van Noorden, 2009), giving weight to the 'RNA world theory'. The first nucleic acids were able to stabilize themselves but only the most effective and efficient methods of data transfer would be selected for and when this was incorporated into a protobiont-like structure, after approximately 1 Ga of selection, the first primitive cell was formed, or if in a protein coat then the first virus would be formed adding further evolutionary pressure to the evolution of the cells (Canchaya, *et al.* 2003; McDaniel, *et al.* 2010). This eventually leads to the last hypothesis of abiogenesis:

The cell is the universal unit of life.

Conclusion

The formulation of a set of hypotheses governing abiogenesis throughout the universe should be able to be inferred as the laws of science are universal. As such the building blocks of life on our planet have been subjected to the same selection pressures as the rest of the universe. The spontaneous formation of the building blocks of life are common place and occur whenever the conditions are right and given enough time simple replicating organisms will eventually be formed.

As such the set of hypotheses governing universal abiogenesis are:

- Any celestial mass that has a body of liquid water and therefore has access to energy, will form at least the building blocks of life, if not life itself.
- The major component of any life form anywhere in the universe will be H_2O.
- Any organism, anywhere in the universe, will be carbon-based.
- All life in the universe will be composed of nucleic acid based molecules as its code for life.
- The cell is the universal unit of life.

This hypothesis will finally be tested when mankind explores planetary bodies like Europa and beyond.

The author understands that the formulation of a universal set of hypotheses governing the formation of life is not a popular view point, but hopes this will help stimulate debate on a universal set of hypotheses governing life in the universe, as these are nothing less than a conclusion of the known laws of science.

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