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AN ASTROPHYSICAL BASIS FOR A UNIVERSAL ORIGIN OF LIFE

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We propose a universal, astrophysically based theory of the origin of life on Earth and on other rocky planets as well. Life is an information system where the information content grows because of selection. It must start with the minimum possible information, or the minimum possible departure from thermodynamic equilibrium. It also requires thermodynamically free energy that is accessible by means of its information content. Hence, for its origin, we look for the most benign circumstance or minimum entropy variations over long times with abundant free energy. The unique location for this condition is the pore space in the first few kilometers of the earth's surface. The free energy is derived from the condensed products of the chemical reactions taking place in the cooling nebula e.g. iron oxides and fixed hydrocarbon, $(CH_2)_{16}$ and the benign environment is the thermal and radiation isolation of the earth's crust. We discuss how this environment occurs naturally and universally astrophysically. We then propose several chemical routes to the formation of life with a minimum entropy departure from thermodynamic equilibrium.[a]

Keywords: Origins of life; thermodynamics and information; star and planet formation.

1. Introduction

The conditions that existed on the surface of all earth-like planets shortly after the time of their formation were extraordinarily harsh. This was during and shortly after the end of planetoid (10 km diameter bodies) bombardment and before the formation of the ozone layer. The rapid emergence of life on earth (a few times 10^8 years following the time when these conditions prevailed), strongly implies that life formed in the protected environment beneath the surface of the Earth as proposed by Gold [17, 18]. This idea is further supported by evidence that the

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litotrophic metabolism proceeded and is more wide spread phylogenetically and geographically than either phototrophy or organothrophy [33]. Thus the most ancient organisms most likely had metabolisms that utilized the free energy from minerals. Even today a large fraction of life, perhaps as much as half of the total biomass, exists in subsurface niches [33]. The large, partially reduced iron ore bodies of biogenic origin (10^{15} tons in the Barberton formation in South Africa) provide evidence for primordial sub-crustal life.

The volume of pore space down to 10 km of the crust (10^9 km^3) provided the vast, protected environment in which life could form. By way of comparison to other feasible environments for the formation of life, the total synthetic potential of just one earth's crust (crust volume $\times$ density $\times$ thermal reaction rate $\times$ time) exceeds, by ~ 4 orders of magnitude, that of all of the molecular clouds, $\sim 10^9 M_\odot$, of the galaxy. (This estimate even excludes the temperature dependence of the reaction rate difference between molecular clouds, 10 deg K and the earths crust, 300 K, which only further exaggerates the preference for a warm, liquid-density environment.) We address the astrophysical question of how the formation of this protected, molecular, and energy-rich environment took place and why we expect this to happen frequently within the galaxy. We estimate that this volume and time available per earth-like planet are sufficient for spontaneous formation of large biologically active molecules or molecular complexes.

In this view the energy source that drives the autocatalytic reactions of the early life forms is the chemical potential difference (redox potential) between hydrocarbons and oxygen. The hydrocarbons are formed in the cooling nebula and fixed as long chain ($\sim$16 saturated hydrocarbons) on the catalysts of various tightly bound silicate grains (olivine) by the Fisher–Tröpsch reaction. The resulting tars coat the grains producing the familiar carbonaceous chrondrites or meteors that still bombard the earth. The oxygen comes from the more weakly bound oxides of iron and sulfides which also accrete as grains to form the planet. The hard silicate grains self-support the pore space against gravitational compression. These same silicate grains coated with hydrocarbon tar and separately iron oxide and sulfide grains supply the free energy for the formation of life in the resulting pore space of various rocks.

In developing this scenario we point out that one crucial piece of evidence would be the presence on Mars of biogenic ore bodies similar to those found in the Earth's crust. Some magnetite ore bodies are biogenic in origin and because of their unique magnetic signature, they are more easily identified. Finally we make the ironic point that the impasse in constructing a logical scenario for the formation of planets by grain, boloid, and planetesimal accretion may reasonably be solved by postulating the important role of inter-grain adhesion by the very hydrocarbons also necessary for life.

The plan of this paper is to summarize the principle arguments in Sec. 1, and then in Sec. 2 we expand upon and summarize the physical and chemical processes leading up to the formation of this crustal environment. In Sec. 3 we expand on the astrophysics leading up to planet formation and then in Sec. 4 we discuss the current evidence for subterranean life and the continuing out gassing of the hydrocarbons of the planet. In Sec. 5 we consider the information theory arguments for the formation of life, and then in Sec. 6 we consider two quite different scenarios of possible chemical reactions leading to the formation of life. These two scenarios span many of the current hypotheses of the origins of life. In Sec. 7 we consider what to look for on Mars for possible evidence of life, and then in Sec. 8 we conclude with the prediction of the universality of life throughout the universe.

2. Overview: Planet Formation, Hydrodynamical and Chemical Processes

The mystery of the origin of life must start with the astrophysical conditions that might lead to the formation of planets of the right size and at the right temperature (distance to the star) to nurture the unlikely event of the formation of life. The particular conditions in a cooling nebula circulating around a nascent sun are critical and unique to planet formation. Many researchers might assume such a nebula as a starting point, because such circumstellar nebula are observed but so also are planets and life observed. Instead we feel compelled to describe a sequence of physical arguments that necessarily leads up to these critical conditions. These astrophysical arguments are generalized, but are important to a predictable theory of star and planet formation. The most controversial will be finding an explanation for the formation of stars from condensations within giant molecular clouds of the Galaxy that will necessarily lead to star formation like the sun and planet formation such as the earth. This will depend upon recognizing a general mechanism for turning on and turning off the transport of angular momentum in Keplerian disks that depends upon a critical mass or surface density thickness of the disk.

Such a critical mass thickness, usually measured in g/cm^2, is not new to astrophysics where cataclysmic variables, stars whose X-ray output varies over orders of magnitude, are uniquely explained by an *ad hoc* assumption of just such a critical mass thickness. The general characteristic of this assumption is that heat generated within the disk, created by the friction of the mechanism for the transport of angular momentum and consequential release of gravitational energy of mass accretion, is contained or confined within the disk for several revolutions of the disk. This leads to a critical mass thickness of $\Sigma_{\rm crit} \simeq 100$ to 1000 g/cm^2. We know of one such mechanism and there may be others yet to be recognized and understood. We have spent considerable effort calculating and understanding the Rossby vortex mechanism for the transport of angular momentum where vortices are excited in Keplerian flow with a radial pressure gradient. The flow of matter through the vortices is well illustrated in Fig. 6 of Ref. 25. The simulation of the damping of these vortices requires a time dependent three-dimensional radiation flow calculation, which has not yet been simulated. Until detailed three-dimensional hydrodynamic calculations are performed with radiation transport, we approximate the critical thickness as

$100\kappa < \Sigma < 1000\kappa$ gm cm^{-2}. Three-dimensional simulations are planned and an experiment is proposed [11] based upon experimental evidence of Rossby vortices in the laboratory. In addition it is well recognonized in meteorology that Rossby vortices dominate the transport of angular momentum in the earth's atmosphere [21]. Finally it has been recently recognized that the same phenomena of Rossby vortex transport has offered a unique solution to the problem of galactic massive central black hole formtation [12].

We feel that without invoking such a critical mass thickness mechanism the conditions for the development of planets and the successive emergence of life will appear *ad hoc*. By invoking such a mechanism we can start our scenario with well observed and less controversial, giant molecular clouds circulating within our galaxy. We then can argue for the conditions for the formation of stars, circumstellar nebulae and planet formation.

Planet formation requires that the right mass of grains and solid material agglomerate to form earth-like mass planets at the right radius from the sun, or star. The radius, an AU, and the luminosity of the star determine the radiation heating from the sun or star and must be such that the radiation equilibrium temperature on the planet and gravity of the planet because of its mass, are such as to keep an atmosphere of gases gravitationally bound to the planet. However, the mass of the planet must not be so large that the pore space in the rock is crushed by the same gravity, thereby expelling all fluids, water and hydrocarbons before life can form. Equally important, the temperature of formation and the equilibrium temperature at the surface must not be so high as to evaporate the hydrocarbons and water from the planet early before life can form. Similarly the surface temperature will effect the temperature of the crustal pore space volume after a thermalization time of $\sim 10^6$ years. In addition, the heat flow from the interior of the planet must not be so great as to destroy molecular life or conversely this same heat flow may possibly sustain life if the surface temperature is so low that after the thermalization time of the crust, that molecular reactions are too slow to form life. All these conditions: stellar luminosity, planetary mass, gravity, radial distance, composition (including a subsequent 5 to 10% hydrocarbon) and temperature we believe are a natural and inevitable consequence of the evolution of the universe.

As a result of this process of gravitational collapse and angular momentum transport, an initially hot, gaseous, and quiescent disk should form provided the heat generated by friction can escape more easily by radiation than by convection. This transition is determined by the critical mass thickness condition where the instability mediated friction in the accretion disk terminates due to loss of heat As the cooling proceeds in a now quiescent disk, some fraction of the matter condenses into grains.

Chemistry starts in the cooling nebula with the formation of the tightly bound refractory oxides and silicates, the latter called olivines. These olivines, generally called rock, play a crucial role in the subsequent chemistry as catalysts for one particular and important reaction, namely the Fisher–Tröpsch reaction that fixes or polymerizes the gaseous, CH_4 form of carbon into long chain hydrocarbons, progressively up to $(CH_2)_{16}$. The isomer distribution expected from the Fisher–Tröpsch reaction has been identified uniquely [1] in the major fraction of the carbonaceous material, which in turn is 5 to 10% of the carbonaceous chrondrite meteorites. Also complex polycyclic hydrocarbons capable of electron transfer in connection with redox reaction are known to exist in these chrondrites. Even today such complex molecules are accreting onto Earth in the form of fine dust particles [10]. The hydrocarbons found in carbonaceous chrondrites are characteristic of the Fischer–Tröpsch reaction. It is assumed that the earth and similar planets are formed from this material. This carbonaceous chrondrite material is sticky and tar-like. We believe that this sticky material plays two crucial roles in the formation of life.

In the cooling nebula, as we have already pointed out, the refractory oxides form first creating the sub-micron size grains, the accumulation of which presumably forms the planet. This process is not entirely obvious. Silicate grains barely adhere to one another with extremely weak binding, so weak indeed that extensive research demonstrates an impossible hypothesis of grain adhesion and growth. Even more enigmatic for planet formation is the destructive boloide collision in the size range of a meter when the boloids are formed within the more massive gaseous nebula. Growth to a meter size by forces of adhesion between silicate grains appears to be impossible. Furthermore if one magically reaches the boloid size by unknown mechanisms, then such boloids of varying size in the differential rotation flow ($\sim$ 10 m/s) of the larger mass of the gaseous hydrogen nebula ensures their break up by energetic collisions. The simple solution to this enigma is to coat the grains with a sticky substance, causing the grains to stick to one another with partially elastic binding. The source of the sticky substance, we believe, is the polymerized hydrocarbons from the Fisher–Tröpsch reaction. The resulting material is then similar to the familiar asphalt of road construction. The elastic-plastic properties of this tar-like material should be more than adequate such that every collision sticks and the larger body grows rather than being destroyed by collisions with smaller bodies. The larger body then grows in size at the expense of the smaller ones with every collision. This causes rapid growth from the micron size of grains in 100 sec, to boloids, a meter in a few years, and to planetoid size, 10 km, in 30,000 years. It is well recognized that once planetoids are formed, gravitational scattering among the planetoids can occur and run away accretion takes place such that all the planetoids within roughly a radius from the star, or sun, accumulate to a planet where gravitational binding prevails. The planet is then formed of silicate grains plus hydrocarbon and various oxides and sulfides. The separation of these disparate materials has happened because of the entropy differences between solid and gaseous states with gravitational mechanical free energy. It is this free energy expressed as the redox potential between the hydrocarbons and the loosely bound oxides that is the free energy source for the formation of life. Finally the mass of the planet will be of the order of the mass of the nebula disk (minus the hydrogen and helium) within the area of the disk of one radius of the disk. The critical mass thickness condition or Rossby vortex mechanism for the transport of angular momentum and hence accretion of the forming star turns off when the thickness of the disk allows the rapid (a revolution time) escape of heat. This in turn corresponds to a mass thickness of about 1000 g/cm^2 H and 100 g/cm^2 of grains. Hence, at an AU radius, the earth distance to the sun, the mass of grains will be area times thickness or $\sim 3 \times 10^{28}$ g, about an earth's mass.

Initially an earth-size planet is presumably composed of a homogeneous amalgamation of carbonaceous chrondrites with some loss by ablation due to heating on impact. Heating in the transition can chemically transform hydrocarbons into more volatile compounds and thus lead to their preferential loss. However, when the planet's gravitational potential is large, resulting in substantial heating on impact, the gravitational binding of the ablated hydrocarbon gases is also high, so an atmosphere of hydrocarbons as well as other gases is likely to form.

We now have formed a warm, 300 K planet where the self-supporting crust is formed of matter with a large free energy. Is there then any catalytic reaction that can access and dissipate this immense reservoir of free energy? The most efficient mechanism for doing so we claim is the formation of life, because, besides a presumed serendipitous catalytic function, it incorporates by definition the possibility of evolution and the consequential increase in information content.

With these preconditions we now give an overview of the two more obvious potential routes to life. The first is where the serendipitous existence of a lipid aggregate, formed by surfactants and the surface tension at the oil-water interfaces. Such aggregates supply a natural, self-assembling structure, where redox reactions can occur across the interface and potentially provide energy to chemical reactions that produce more surfactant molecules. Also, information containing sequences of molecules can naturally self-organize at the interface in particular if they themselves are surfactants of if they have the opposite charge of the interface layer. The second, more brute force approach, is where the minimum templating sequence formed serendipitously in the "soup" and where its information content is sufficient to carry catalytic action, template reproduction, and contain sufficient redundancy of information such that there exist several adjacent workable alternate information sequences in order to initiate evolution.

We now expand the astrophysical arguments that lead to a rocky planet and subsequently we discuss these possible routes to life within the planetary pore space, a unique and diverse chemical reservoir with constant temperature and abundant free energy.

3. The Astrophysical Formation Mechanisms

3.1. *Star formation*

The mystery of the origin of a star of a solar mass is the first question we need to address in the quest for a logical physical sequence of explanation starting from the origin of the universe to the origin of life. Star formation is a mystery because it is not fully understood, yet it is universally assumed that star formation must depend upon well tested classical physics. So far all explanations (see the seminal reviews in Ref. 43 and the recent summary in Ref. 34) have been too complex to lead to a simplified coherent model. We start with the condition described as "molecular cloud cores". Molecular cloud cores are over dense regions within molecular clouds [3]. The mass distribution of the these cores is well defined and leads to a power law $dN(m)/dm \propto m^{-\alpha}$ with $\alpha \simeq 1.6$, a value far flatter than the IMF (Initial Mass Function, or number of stars versus their mass in the galaxy), where $\alpha \simeq 2.5$. Thus the implication is that clusters of stars form from individual collapsing cores. There are then two somewhat divergent views as to how this may happen. In Refs. 42 and 24 they argue that a singular isothermal sphere (SIS) model, leads to an "inside-out" collapse of the envelope onto a protostar. Such a collapse is driven by a rarefaction wave at the inner boundary of the envelope and reverses or terminates presumably due to both gas pressure and radiation from the forming star. Such models have problems in finding a satisfactory equation of state and in deriving sufficient radiation to reverse the in-fall. Thus one has been led to possible feedback models that terminate collapse because of large, partially collimated outflows, that occur for no apparent physical reason. In other words these collapses of the cores terminate with only a fraction of the original mass forming a star because of feedback from an unknown cause. One desires a feed-back model based upon a robust physical reason.

Our view is that cores collapse until the matter is supported in a disk due to its initial angular momentum. At some point in the radius of the resulting distribution of disk matter, the critical mass thickness condition or Rossby vortex mechanism commences due to the increasing disk mass thickness with decreasing radius, or $\Sigma_{\rm disk} \propto 1/R$ and also due to the radial pressure gradient. When this happens all the matter inside this point of instability can exchange angular momentum with matter outside and therefore collapse to form the star. The origin and distribution of angular momentum of the cores happens because the cores, being more condensed objects, gravitationally scatter just as is predicted and observed for the giant Lyman-alpha clouds that precede galaxy formation. The scattering leads to random rotation. The magnitude of the rotation is measured by the ratio of the spin of the cloud from tidal torquing versus that of a Keplerian orbit at that radius and that mass, or $\lambda_{\rm cloud} = v_{\rm cloud}/v_{\rm Keplerian}$. It turns out that tidal torquing leads to a universal $\lambda_{\rm cloud} \simeq 0.1$. Since this is also proportional to the angular momentum and angular momentum is conserved during collapse, one can predict the radius and thickness of the equilibrium Keplerian disk with this specific angular momentum. This thickness, $\Sigma_{\rm disk} \propto 1/R$, and so there is some radius and mass fraction where the critical mass thickness instability initiates, presumably $\Sigma_{\rm disk} \simeq 10^3(1/R)$ g/cm^2 because of the relative transparency of the major constituents, H and He. Then nearly all the mass interior to this radius collapses to form the star. The residue of the disk is determined by the condition that when the mass flow depletes the mass in the disk to the point where the thickness is less than the critical value for the instability, or the above value of $\Sigma_{\rm disk} \simeq 10^3(1/R)$ g/cm^2. This describes the nebula, now cooling because of the termination of frictional accretion heating and hence, the start of planet formation.

3.2. *Angular momentum transport, and the critical mass thickness vortex torquing*

Key to this explanation is the recognition of the role of a critical mass thickness. We see at least one possible mechanism, Rossby vortex excitation for the transport of angular momentum in accretion disks. We recognize that magnetic fields, gravitational tidal torquing, and an *ad hoc* α-viscosity may all play a role, but we have singled out the critical mass thickness condition as explained by the Rossby vortex mechanism or vortex torquing as important. (See the result of a 2D full 2π, nonlinear calculations [25].)

The turn-off condition of vortex torquing is also the same as the precondition that turns it on. This condition is a sufficient mass thickness of the disk so that the co-rotating vortex motion is adiabatic or isentropic. This ensures that the radial motions of a co-rotating vortex within the disk are reversible without a large irreversible PdV dissipation. A condition for this to be the case is that there is a minimum radiation thickness of the disk to contain the heat long enough so that the motions within the disk are isentropic for several rotation periods. If one has less than this radiation thickness and thus large dissipation of the vortices, then they will rapidly damp and not be excited and there will be no vortex torquing. Hence there is a mass thickness, below which the disk is an ensemble of quasi-isolated stable Keplerian orbits that cool and do not interact. Hence the turn-off condition of this disk is a combination of opacity and mass per unit area. This in turn defines the post formation stellar nebula and thus the nebula mass from which planets form.

3.3. *The stellar nebular and the planet masses*

The precondition of this nebula is the starting point for almost all modern discussions of the solar system and is the nebula assumption of Ref. 8, and Ref. 38 where a Keplerian disk of $0.02M_\odot$ surrounds the already formed sun. It is likely that the critical mass thickness condition mediates the formation of all stars and therefore is the physical key to understanding the IMF, "initial mass function," or $dN_{\rm stars}/dM_{\rm stars}$. For now, however, we concern ourselves with the formation of the planets and how this naturally leads to the preconditions for the origin of life.

3.4. *The mass barrier in planet formation*

The turn-off condition of the Rossby instability of the confinement of the heat leaves a quiescent disk of thickness $\Sigma \simeq 10^3$ g cm^{-2}. This thickness times the disk area at 1 AU becomes 6×10^{29} g or $\simeq 30 \times$ the earth's mass. The nebula mass is primarily H and He so that the remainder of heavier elements accounts for the non-volatile mass of the earth and also the opacity that determines the thickness. This cooling nebula at 300–600° K then starts the condensation to grains. Earlier, with more mass and heat confinement, the temperature is too high for grain formation. The Rossby vortex α mechanism would continue to sweep all this volatile disk mass into the forming sun until the instability turns off. Then grains of sub micron size form as condensates. However, accumulating masses larger than this is a long standing problem. As Blum with 21 colleagues lament [7]:

> "The outcome of the first stage of planetary formation, which is characterized by ballistic agglomeration of preplanetary dust grains due to Brownian motion is the free molecular flow regime of the solar nebula, is still somewhat speculative."

And this is for particles of a few 10's of microns in size. The real problem becomes truly insuperable at meter size boloids. As Ref. 46 derives in great detail, the collision velocities of boloids maximizes at meter sizes. Boloids of sizes a factor of two apart develop differential velocities of $\sim 3 \times 10^3$ cm/s. The relative energy densities of colliding boloids becomes up to 10^7 ergs/g. In contrast, the fragmentation energies of the fragile agglomerates of the space experiments [7] are of order 10^{-4} ergs/g. Thus the impact energies and the fragmentation energies are eleven orders of magnitude apart. The author of Ref. 4 have calculated the collision density of the impacts using Wiëdenshilling's distributions and there seems to be no way to avoid this collision destruction barrier. Many have been looking for a way out of this dilemma. We believe we have found a solution in the stickiness and *elasticity* of the tar-like material that forms the hydrocarbon of carbonaceous chrondrites. This material has been shown by Ref. 1 to be synthesized by the Fisher–Tröpsch reaction on grains of olivine using CO, CO_2 and H_2O. The polymerization proceeds until the carbon chain is long enough so that the vapor pressure is low enough to attach to the grain as a non-evaporating tar. This is how the elastic glues of tapes are made in modern industrial processes and where the polymerization proceeds until the tar is formed. The energy of disruption of this elastic sticky coating we believe is sufficient to bridge the collision destruction barrier and lead to the formation of gravitationally bound planitesimals, (sizes $> \sim 10$ km) followed by the run-away gravitational accretion to a planet. The extent to which this hydrocarbon reaches the forming planet has yet to be agreed upon, but it should start at the remarkably high percentage of $\sim 5\%$, which is quite adequate to hold a mixed, heterogeneous elasto-plastic material together. (This percentage is the percentage of tar in asphalt.) It may be one more irony in the formation of life that the breaching of the collision barrier of boloids can be explained by the same materials as is later needed for building blocks to form life.

4. Evidence for Subterranean Life and the Presence of Early Hydrocarbons

The strongest current evidence for hydrocarbon trapping is the present slow outgassing of the earth: (i) the continental scale of correlations in Earth gas composition ratios. These gas composition ratios include the hydrocarbons, carbon dioxide, nitrogen and the inert radiogenic gases, which are independent of large local stratigraphic variations; (ii) that petroleum and methane are frequently found in geographic patterns forming arcs related to deep large-scale features of the crust [17]; (iii) that deep earthquakes, several minutes in duration, have been detected below 600 km and might be explained by a lighter, Rayleigh–Taylor unstable fluid rising relative to an elastic-plastic medium; (iv) the evidence for high temperature life. Just the existence of anaerobic, thermophilic bacteria [40], some of which digest oil [44] suggests subterranean life is not that rare. These life forms are considered phylogenetically very ancient and has been collected from hydrothermal vents and undersea volcanic eruptions [19]; (v) the Barberton pyrite formation, a $\sim 10^{15}$ ton biogenic iron based ore body in South Africa, pointing to a vast biosphere only several hundred million years following the end of meteoritic bombardment of Earth [31]; (vi) the magnetite ore body found six kilometers below the Siljan Ring in the granite of Sweden, which points to a biogenic origin because of the peculiar form of the magnetite, namely sub-micron grains. Grains of magnetite are formed by known paleobacteria when feeding upon iron sulfate and Fe_{2O_3} dispersed in classical petroleum [18].

5. The Information Argument or Why the Most Gentle Conditions for the Origin of Life

Life is an information system that accesses and enhances the dissipation of the free energy of the universe. The following information theoretic arguments concerning life help define the likely site of its origin.

There are four fundamental theorems or laws of information:

(i) *Szilard*: *Entropy and information are equivalent*

When information is thrown away, heat is generated in the process, a higher entropy of the lost information. The remainder, the information, is greater, cooler, and has lower entropy. A Carnot engine might be run between these hot and cold baths and gain "useful" energy, a perpetual motion machine, unless, and at least, an equivalent amount of work was done in performing the decision to throw away the discarded fraction of information.

Example: A box of gas is divided in two with a door operated by Maxwell's demon who opens the door for hot, energetic molecules and closes the door, reflecting, the low energy cold molecules. In this way the demon creates a separated hot and cold gas in the two regions. Why not run an engine between these two regions and gain useful work, a perpetual motion machine? This violates the second law of thermodynamics. Explanation: Maxwell's demon generates as much entropy (heat) from throwing away the information of the decision of operating the door as can be gained from the hot or cold baths, i.e. the second law of thermodynamics: you cannot make a perpetual motion machine (of the second kind). Therefore information and entropy are equivalent.

Since life requires information, it must create a local reduction in entropy. This requires energy. Therefore life must utilize free energy. The local increase in information content or decrease in entropy occurs by the decision process of survival. The decision leading to survival is the basic computation of life. This decision "navigates the Entropy Landscape of Life."

(ii) *Turing, the computability theorem*

Our basic assumption and description is that life is an information system. Thermodynamically we always expect heat to thermally degrade information (an increase in the entropy of the system). Thus in order to combat this degredation, in order for life to prevail, there must be a mechanism to increase its information content. Such a mechanism is equivalent to computation. In computation a decision is made to throw away part of the information content so that what is left has a higher information content, e.g. addition, where one number is the result and the identity of the two or more addends are lost. Therefore if life can perform a computation, in essence it must operate as a computer, which is what the Church Turing thesis implies. The initial algorithm of computation by life is survival. It leads to the decision to throw away a fraction of the information content so that what is left has a higher information content. Thus the possibility of evolution is fundamental to the initial conditions for life. Turing has pointed out that the exact form of the computer is irrelevant in that given a computer, any computer can compute anything given enough time with some limitations expressed by the Halting problem. However, in a practical sense, there appears to be no limit to what can be computed. Thus once life can compute, life is not limited by computation. Thus contrary to ecological resources, there are no practical limits to the information content of a system. The Computability Theorem says so: Anything that is information can be computed. Therefore any and all decisions can be made. Therefore there are no inherent information processing limits to life.

(iii) *Shannon, the transmission theorem*

There are no limits to the transmission of the information of life, i.e. reproduction.

All information can be transmitted with arbitrarily high reliability given channels, frequency, and redundancy. DNA is one such system that works remarkably well, but there can be an infinite number of others among which there may be a better one. DNA is a very durable molecule. Hence, genetics is based on DNA versus the more fragile RNA, which may have preceded DNA, or in turn preceded by PNA, which may have preceded RNA etc.

(iv) *Goedel's incompleteness theorem*

No logic system is both complete and consistent. If it is complete one can show p and $\sim p$ (Hilbert's 1st problem). Therefore there are no limits imposed by logic on an information system.

Since these four theorems on information alone should not limit life, how is it that it took so long, a Hubble time, to emerge? This emergence requires the unusual properties of a system of: *access to free energy*, *computation*, and *stable transmission* (of information). To surmount the unlikelyhood of this combination by chemical mechanisms alone (there may be others) requires a *source of free energy*, *time*, and *protection*, which is why we point to the planetary pore space as the most likely place for the origin of life: *free energy for computation*, *time for chemical reactions to occur*, and *protection from entropy increasing processes*, e.g. thermalization. In this view Von Neumann's self-replicating machines, or molecular self-replicators are a necessary, but insufficient step towards life without including a variability in the inherited specification and stability of the reproduction, permitting the computation by selection. However, if a Von Neumann self-replicating machine or a molecular self-replicator were to emerge, they might very well be endowed with the properties of computation and the necessary accessibility of free energy. We only wish to enumerate here all these simultaneous requirements that we believe are necessary for the emergence of life and thus the specification of a possible environment in which this is likely to have occured. To a great extent Von Neumann's work on self-replicating machines has been the starting point for the last twenty years of activities, e.g. within the artificial life community. However, this activity has not paid much attention to the relation between free energy, information, and the stability of informtion transmission as it relates to the origin of the first molecular self-replicators.

6. Formation of Life

Our scenario suggests an early Earth with a crust with a pore space rich in hydrocarbons, water, and minerals, which contains large deposits of iron oxides, much as it does today. The porous volume involved is so large that building blocks for almost any polymer had ample time to form in many different combinations — allowing ample opportunity for the emergence of complex polymers or polymer aggregates capable of autocatalytic replication.

The pore space gives life many possible starting points. We present two different pictures that span a variety of possibilities. The assumption in the first picture is that a single unlikely or limiting event has to occur and in the second picture several not quite as unlikely events have to co-occur. In both pictures the spontaneous formation of a templating polymer is necessary. In the first picture the templating polymer is assumed to be self-replicating, which probably requires a rather long polymer to obtain the necessary functionality. In the second picture, the templating polymer does not need to be very long, but it has to coexist with lipid aggregates hosting certain redox molecules, were the combined likelihood of such an aggregate may be just as unlikely as the emergence of a single self-replicator.

Many other possible pathways for the origins of life have been proposed either based on proteins first [32], genes first (see e.g. Ref. 16), or lipids first (see e.g.

Refs. 26 and 45). In the theoretical discussions of these pathways it is either assumed that a single, highly unlikely event has to occur or several perhaps not quite as unlikely events have to co-occur. Theoretical discussions have mostly focused on the latter tradition: For example Kauffman [23] and Farmer *et al.* [15] argue that autocatalytic sets, cooperative structures of mutually catalyzing polymers, are the key stepping stone for the origin of life. The appeal of this argument is that under certain conditions the probability of mutual catalysis grows faster than the decay processes the more species are present. Thus the system goes "critical" if enough different species is present at the onset or if we wait long enough, assuming that more and more polymers are spontaneously created. The question is whether enough pre-biotic polymers of the right kind can spontaneously congregate in one location? This is an example of a theory where multiple rare events have to co-occur. In 1971 Eigen [14] proposed that hypercycles, cooperative structures of self-replicating RNA systems, are a key stepping stone for life. Eigen did that to address the "information catastrophy", which is due to the sloppy copying of proto-genes without enzymes. Any encoded information "melts" away before the proto-genes reaches a significant length. Rasmussen [35] later calculated the expected time of emergence of such hypercycles, which again is based on multiple co-occurring events. Recently an autocatalytic model of lipid self-assembly and successive lipid production has been proposed by Sagre *et al.*, which also relys on multiple co-occuring events.

For both of the pictures of the origins of life we present, it is interesting to note that in an aqueous environment key building blocks of modern life such as peptides and oligomers, will not spontaneously polymerize. The free energy is biased towards the monomers due to the release of a water molecule in the process. Lipids, which are also important molecules of life, are different in their chemistry, since in their simplest form, they can be transformed directly from hydrocarbons. It is actually likely that surfactants (simple lipids) were present in ample amounts at the early Earth because they have been found on carbonaceous chrondrites [13]. The original spontaneous reactions that formed templating polymers could have happened in the essentially water-free environment of an oil-droplet if the monomers were hydrophobic, or a micellar or vesicle surface could have acted as a catalyst.

For the self-replicating polymer, we assume there exist a small number of different monomers capable of polymerizing into long chain molecules, some of which could be templating. We rely on random processes alone to form those molecules and we obtain a simple estimate suggesting that the start of life may not be that unlikely an event. To obtain such an estimate we assume that the monomers were present at concentration below parts per billion. As pointed out by Cairns-Smith [9], however, it is not necessary for life to start with the same building blocks that are found today, and we do not speculate about the identity of these monomers. However, to be specific we assumed 10^{12} molecules/g of rock. If we further assume that the dimer concentration is half of the monomer concentration (which would depend on the degree to which this process is thermodynamically uphill) we find from a simple polymerization equation, the equilibrium concentrations of all the polymers. A rough approximation to the solution of the steady state polymerization equation is that the n-mer is present at a level of 2^{-n+1} of the monomer. The concentration ratio is related to the free energy released in the polymerization reaction and would imply a bond strength of less than that of a single C–C covalent bond (< 300 kJ/mol). How complex a self-replicating molecule has to be is not entirely clear. For the purpose of this discussion we suggest that among all templating chains of length fifty, one may be capable of catalyzing a template directed self-replication. For our simple model we restate this assumption in the form: the most simple autocatalytic polymer involves 50 monomers and among all different combinations of monomers 1 in 4^{50} (four different bases) is capable of self-replication. If we further assume that the life time of a 50-mer is of the order of 1000 seconds and that a layer one kilometer thick all around Earth is involved in this process we find that in 300 million years, 10,000 autocatalytic polymer chains will have been formed spontaneously. Once formed any one can then proceed to form more copies of themselves and the most simple form of life has begun.

If we assume this proto-gene to be similar to, e.g. RNA, which has a charged backbone, an opposite charged mineral, a lipid surface, or ice [2, 28] could mitigate the template directed polymerization process after the appearance of the first self-replicator. Using the slight free energy advantage from the attachment to such interfaces, would then be the first "metabolic" driver. Later, these delicate self-replications had to develop a catalytic cooperation with a more substantial chemical energy source through a redox complex. However, much experimental effort has been put into developing RNA that catalyzes its own replication, which has turned out to be very difficult and only moderately successful [22]. It is still an open experimental question whether self-replicating RNA molecules exist.

Still developing the same picture, if we now assume the templating molecules to be surfactants, e.g. to have a hydrophobic backbone, as a lipophilic peptide nucleic acid (PNA) [30], some of the above problems may diminish. First of all PNA is easier to synthesize under pre-biotic conditions, but more importantly, thermodynamics would force PNA's hydrophobic backbone into an oil-droplet or lipid aggregate, where it could polymerize, through peptide (amide) bond formation in this more favorable environment [6]. Since water is nearby it could allow the spontaneous formation of templating polymers in the hydrocarbon-phase while the template directed self-replication is performed at the water-lipid (or oil) interface all present within the same rock pore. Although the thermodynamic conditions seems much more favorable for a PNA-like proto-gene, the emergence of a single self-replicator still faces the same kind of challenges in terms of coupling to a more significant metabolic driver than the free energy associated with the interfaces.

An alternative picture assumes that initially simple polycyclic hydrocarbons (PCH), which are hydrophobic, started inefficient redox reactions within surfactant aggregates fueled by the fugacity in the minerals. For example, carbon could be oxidized with Fe_2O_3 providing the oxygen. Assuming these redox reactions generated more surfactants, more PCH could be absorbed to produce even more surfactants and so on. Other reactions involving oxygen, iron, and sulfur can be envisioned to provide the energy for such first metabolisms [19]. Since most surfactants typically generate higher order aggregates of specific sizes these aggregates most likely will divide and form new aggregates as they grow. A variety of experimental systems have been developed by Luisi and co-workers verifying related processes [26]. If such a system explores redox reactions with the ability to modify certain PCHs into better redox molecules, a powerful autocatalytic system is created as lipids and redox molecules mutually support each others production. Such a system is similar in spirit to the autocatalytic lipid system proposed in Ref. 39. If such an redox aggregate was also able to synthesize surfactants that can polymerize and template, as for example PNA-like monomers, an even more interesting systems could emerge.

Although such self-reproducing surfactant/metabolic processes are interesting cooperative physicochemical systems, they hardly qualify as living processes. If we believe that such proto-metabolic processes are likely to form due to the rich pool of HC and PCH as well as nonequilibrium chemical energy bound in the minerals, a short PNA-like template (say a 10-mer) could attach to such a metabolic aggregate. Now, if it so happens that this PNA molecule has a unique base sequence that "encodes" a higher efficiency of the already slowly running redox reactions — which could either be a direct chemical influence, e.g. due to the chemical properties of the bases, or it could, e.g. be due to the geometry of the PNA strings specific folding — a significant coupling has been established: The PNA enhances the production of surfactants and thereby the lipid interface, which is needed for the PNA to polymerize and replicate, and which is also necessary for the redox processes to occur. An autocatalytic feedback loop is closed and its efficiency is "encoded" in a templating proto-gene and can thus be propagated to the next generation and evolution is now possible. It would be even better if the PNA-like string could also enhance the production of PNA-like monomer surfactants that can polymerize and template it would also produce monomers for its own replication. It is still an open experimental question whether short PNA strings can replicate at a lipid water interface.

Such a system is clearly capable of Darwinian evolution — assuming two different PNA sequences residing on two different aggregates. Obviously the PNA that is speeding up the redox kinetics will produce more interface (and redox complexes), which helps it template more copies of itself. The growing number of surfactant molecules will eventually bud off producing separate aggregates carrying a few of the new PNA molecules and this process will continue until the whole system is taken over by this coupled PNA-redox-lipid-aggregate system.

A detailed experimental and theoretical discussion of assembling a proto-organism similar to this second picture can be found in Ref. 36, and a discussion of the replication kinetics and the coupling between the proto-genes and the lipid aggregate can be found in Ref. 37.

Clearly it is much more likely for a PNA 10-mer (probability P_{10}) to spontaneously polymerize than it is to have an PNA or RNA 50-mer (probability P_{50}) to emerge. Using the arguments and assumptions from the first picture we find that $P_{10} \sim 10^{24} P_{50}$. Today the planetary crust contains about 200 ppm of carbon and some four billion years ago only a small fraction of this carbon would have been available (from outgassing) in a liquid hydrocarbon form, maybe 1 ppm of the available C to be conservative. Even a smaller fraction of the liquid hydrocarbon would have an appropriate surfactant concentration together with a mixture of PCH, perhaps 1 ppm of the available liquid hydrocarbons. Thus, we could speculate that the probability of being at a location near mixtures of liquid hydrocarbons, surfactants, polycyclic hydrocarbons, and water anywhere in the crust is about $2 \times 10^{-4} \times 10^{-6} \times 10^{-6} \sim 10^{-16}$. With these numbers we should expect 10^{10} independent occurrences of coupled PNA-redox-lipid-aggregates over a 300 million year period.

Both of the above pictures are certainly too simplified and leave out many important details in this presentation. In particular we have not argued how these key polymers and aggregates interact with the multitude of other chemical species presumably present in the pre-biotic environment. Neither have we argued for particular synthetic pathways. However, both pictures show that the pore volume provides a unique environment which overcomes many of the difficulties perceived in alternative origins of life pictures.

First the sheer volume makes spontaneous formation of complex molecules much more likely; the intimate intermingling of water-free and aqueous environments overcomes the difficulty that the standard building blocks of life cannot spontaneously combine to a complex molecule or molecular complexes, while at the same time, the spontaneous and uncontrolled attachment of monomers to a growing chain nearly certainly will destroy any autocatalytic process that depends on its ability to control the species of the next monomer. In this sense the natural separation of hydrocarbons and water inside a pore performs the functions of micelles or coacervate drops, or alternatively such lipid structures could also be present there. Small lipid aggregates are advocated by many authors in the field: Oparin [32], Morowitz and Deamer [29], and Luisi [26].

Second, the pore volume brings together hydrocarbons, complex organics, catalytic interfaces and surfaces, as well as various iron oxides and sulfides. This environment allows for many chemical reactions that can provide the energy to fuel the autocatalytic reaction which raises the concentration of active molecules far beyond that expected in thermal equilibrium.

Third, the subterranean volume provides significant protection against harsh surface conditions. This could explain why well-formed life can be found in some of the oldest sediments.

This last problem would be exacerbated if the recent assertion of McCulloch held [27]. Based on the discrepancy between lunar and terrestrial Sr isotope ratios he concludes that the moon was formed long before the accretion of Earth was complete and suggests that the accretion period may have lasted well beyond 4.4 billion years ago. Fossils, however, indicate the presence of already well developed surface life as early as 3.5 billion years ago [41].

7. The Odds for Past and Present Life on Mars

We have outlined our scenario which suggest a natural progression from abiotic, organic matter in the early planetary cloud to the origin of simple subsurface life on Earth. It appears likely that a similar chain of events should have occurred on Mars. We will try to strengthen this comparison by investigating the hydrocarbon accumulation as function of location in the planetary cloud and as function of the size of the protoplanet.

Thus, it appears reasonable to ask whether Mars at any stage of its development supported subsurface life. A search for subsurface life must begin by looking for the largest effect such life would have on its environment. The biggest impact of subsurface life would surely be due to its need for energy. Subsurface life almost certainly will involve iron or sulfur in its oxidation and reduction processes. Thus, mineral deposits might serve as a pointer for future investigations. Among those mineral deposits, magnetite seems a most likely candidate, because it is frequently of biogenic origin on Earth, but also maghemite, and the iron sulfides, greigite (Fe_3S_4) and pyrrhotite (Fe_7S_8) are possible candidates.

Furthermore, because of magnetite's high magnetic susceptibility, it has a clear magnetic signature. Magnetite deposits, such as those found in Kiruna not too far from the Siljan ring, should be detectable even kilometers below the surface and even with the small ambient magnetic fields found on Mars. A search for such deposits could commence from the ground or from planes roving the Martian atmosphere. The detection of significant magnetite deposits would point the way for future experiments that could unambiguously establish the biological origin of such deposits.

Possible life on Mars today would undoubtedly be linked to the presence of water and it would most likely be microbial chemolitothrophes. As on Earth, possible Martian chemolitotrophes could metabolize a variety of compounds, e.g. S, SH_2, Fe^{2+}, NH_4, and H_2. Thus the most promising landing sites on Mars would be places with a high magnetic signature, e.g. from magnetite, combined with shallow ground water deposits, and the presence of subsurface redox energy. In general, consistency indicators for subsurface life are ground water regions with highly depleted (close to thermodynamical equilibrium) mineral components when compared to the expected weathering processes.

8. Conclusion

If this rather complicated scenario proves robust, then life should be ubiquitous in rocky bodies throughout all galaxies of the universe.

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