Astrobiology Perspectives on Life of the Universe

Conflicting Models for the Origin of Life

Edited by

S.K. Smoukov, J. Seckbach, & R. Gordon

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Astrobiology Perspectives on Life of the Universe

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In his 1687 book *Principia*, Isaac Newton showed how a body launched atop a tall mountain parallel to the ground would circle the Earth. Many of us are old enough to have witnessed the realization of this dream in the launch of Sputnik in 1957. Since then our ability to enter, view and understand the Universe has increased dramatically. A great race is on to discover real extraterrestrial life, and to understand our origins, whether on Earth or elsewhere. We take part of the title for this new series of books from the pioneering thoughts of Svante Arrhenius, who reviewed this quest in his 1909 book *The Life of the Universe as Conceived by Man from the Earliest Ages to the Present Time*. The volumes in Astrobiology Perspectives on Life of the Universe will each delve into an aspect of this adventure, with chapters by those who are involved in it, as well as careful observers and assessors of our progress. Guest editors are invited from time to time, and all chapters are peer-reviewed.

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Conflicting Models for the Origin of Life

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Foreword

https://winstonchurchill.hillsdale.edu/men-moon-churchill-alien-life-1942/

"Are There Men on the Moon?"
by Winston S. Churchill

Text from Michael Wolff, ed., *The Collected Essays of Sir Winston Churchill,* vol. 4, *Churchill at Large* (London: Library of Imperial History, 1975), IV 493-98. Reproduced courtesy of the Estate of Winston S. Churchill by permission of Curtis Brown Group Ltd.

Does life exist elsewhere in the Universe? Indeed a fascinating question. All living things of the type we know require water, not only because some of them want it to drink or, in the case of marine animals, to live and swim in, but because every living unit, animal or vegetable, consists to a very considerable extent of this fluid.

Now one cannot altogether rule out the possibility of a totally different world with oceans of some other liquid, such as petrol or, as some might perhaps prefer, alcohol, in which a weird and complex organic synthesis has brought into being units which one might call "living creatures." But nothing in our present knowledge entitles us to make such an assumption. Of one thing, however, we can be certain, and that is that any entities formed in such surroundings would be totally unlike anything we know under the guise of living creatures or plants.

Now, if we confine ourselves to the sorts of things we know and admit that water is a necessary ingredient of their life and being, we are restricted within comparatively narrow limits in the conditions in which such entities can exist. As we all know, if it is too hot, water boils. Even the most meagre acquaintance with hygiene tells us that the best way to sterilize anything is to dip it in boiling water. On the other hand, if the surroundings are too cold, water freezes, and it is difficult to imagine that life could ever be formed in a world of ice and snow, even though creatures, developed from types which were produced in kinder surroundings, have managed to survive in arctic regions.

Briefly, then, if life in the form we know it is to exist anywhere, it can only be in regions of comparatively moderate temperature, say between a few degrees of frost and the boiling point of water. Obviously, the stars are completely ruled out for this reason. For these consist of gigantic masses of incandescent gas in which every chemical compound is split up in its simplest components and in which the mere idea of life is an absurdity.

But the sun, which is a comparatively insignificant star in the Milky Way—which is the name we give to our galaxy—is surrounded, as we know, by planets of which our world is one. On our earth life has developed. It has been able to do this because the temperature is neither too high nor too low. It is very easy to see what fixes the temperature of our earth. It is the temperature at which the heat falling upon it from the sun is equal to the heat which it radiates away into outer space. If it gained more than it lost it would get hotter, until the export of heat equaled the import, and vice versa. Mathematicians have an exact way of calculating this. But even without mathematics, it is clear that if the earth were further away from the sun it would receive less heat and therefore that its temperature would be lower.

From these considerations alone it is safe to rule out what are known as the outer planets—Jupiter, Saturn, Uranus, Neptune, and the recently discovered Pluto—as possible abodes of life. There remain Mars, Venus, and Mercury. The mean temperature of Mars is well below the freezing point of water. It is a cold, arid planet with a climate somewhat like the top of Mount Everest would be if the sun were partly obscured, but with much less ice owing to a shortage of water. Life may exist there; indeed, the changes of color in its spring and winter seem to indicate that some form of vegetation—be it only lichen—enlivens the faintly sunlit landscape. But the circumstances are harsh and forbidding, the atmosphere is thin and dry and short of oxygen, and there is little reason to suppose that any very highly organized forms are likely to have arisen.

Venus, on the other hand, being nearer to the sun, is considerably warmer than we are. Apparently, there is moisture in plenty, indeed, from our point of view, too much. For it is covered with a perpetual layer of cloud which prevents us seeing what the surface may be like. Though there does not seem to be much evidence of oxygen, it may be that in this hothouse atmosphere an elaborate flora and fauna exist, perhaps even intelligent beings. But unless they have developed some form of aeroplane which enables them to rise above the clouds, it is quite possible that if such intellectual creatures live there, they are quite unaware of the existence of an immense and complex universe of stars and nebulae outside their own world, and that they are living in the egocentric belief that they are the one and only habitation fit for reasoning beings.

On Mercury, the innermost planet, it seems unlikely that life has arisen. Water would boil on the sunny side, while the face remote from the sun is so cold that most of the planet's surface would be intolerable for any living entity we know.

But what, it may be asked, of the moon? Our own satellite approximately the same distance from the sun as we are, and whose temperature therefore must be about the same as our own. This brings us to another condition which must be fulfilled if water and any sort of atmosphere are to persist. Any form of gas or vapor, as we know, consists of a lot of small particles, so-called molecules, flying about at high speeds, bumping into one another and against any solid or liquid with which they are in contact. The hotter the gas, the faster they move; indeed, when we say that it is a hot day, what we really mean is that the molecules in the air are moving faster than usual. Now, it may seem strange that these molecules flying about in the outmost layers of the atmosphere do not simply shoot away into space; for, after all, there is no lid on the top of the atmosphere to stop them. The reason they do not is simply what we call the force of gravity. If you throw a stone into the air, the reason it falls down and does not go straight on is because it is pulled back by the earth. In the same way, a molecule at the top of the atmosphere does not fly away because the earth attracts it, and it falls back again.

Now, the moon is very much smaller than the earth, and the force with which it attracts anything is therefore less. A man who could throw a cricket ball a hundred yards on the earth could throw it six hundred on the moon. The molecules in the atmosphere, which find it impossible to escape from the earth, would readily fly away from the moon's surface; indeed, such atmosphere as it may have had in the beginning has almost completely vanished. Thus the moon is an arid desert, almost entirely bereft of air or water, on which only the lowest forms of life can possibly exist.

This argument applies, of course, even more strictly to the small fragmentary planets called the asteroids, a group of hundreds of little units ranging from about four hundred miles in diameter downwards which circle round the sun in orbits between that of the earth and Mars. Even the largest, with an area of some hundreds of millions of acres—which might at first sight appear to be an agreeable refuge in these unpleasant times, if only one could get there—is completely ruled out for any normal form of life by the smallness of the gravitational force which exists on its surface. On the smaller ones it would be possible to drive a golf ball right away into space; indeed, a man would run some risk if he jumped over an obstacle of flying away from his world altogether and himself becoming a planetoid circling round the sun.

But, of course, nobody could live on such a tiny world, as no air or water could possibly remain on its surface, where the pull of gravity is so minute. In our own solar system, therefore, we can say fairly definitely that life of any complexity can exist outside our own earth only on Venus or Mars.

But what about planets surrounding the other stars? The sun is merely one star in our galaxy, which contains several thousand millions of others. At first sight it might appear obvious that these others may be presumed to possess planets, which, if they happen to be at an appropriate distance and of the proper size, may be surrounded by atmospheres and be watered by rain as we are. This is probably true of a large number, though doubt has been cast upon it for a rather interesting reason. Astronomers for over a hundred years have been trying to account for the fact that there are all these planets surrounding the sun. They are all of them moving in much the same plane and in the same direction. Surely this should provide a clue.

Now one of the explanations which has found great favor is that they were formed by the close approach to our sun of some vagrant star. This would attract gas on the surface and form a huge tidal wave which, if the star were sufficiently large and sufficiently close, might be dragged out of the sun and form a splutter of gas which would condense ultimately into a series of planets. Now, if this was the origin of the planets, it is possible to work out how near the vagrant star must have come, and it is found that the approach must have been very close indeed.

But we know how many stars there are, how far they are apart, and how fast they move. One can work out, therefore, what the chances are of a close approach of this nature. Roughly speaking, if we made a model in which our world was the size of a grain of sand, the sun would be about the size of a golf ball, and its nearest neighbor would be represented by another golf ball about three hundred miles away. It is obvious that in such circumstances the chance of a clash is very small—so small, in fact, that it has been computed that only one such clash was likely to occur even amidst all our thousands of millions of stars in a thousand million years. If this is so, our sun may be indeed exceptional and possibly unique; no other star, or very few, would possess a family of planets, and *a fortiori*, no other planet would be the home of life.

But this speculation depends upon the hypothesis that planets were formed in this way. Perhaps they were not. We know there are millions of double stars, and if they could be formed, why not planetary systems? Anyhow, many astronomers believe that all the stars were much closer together some few thousand million years ago, so that these close encounters would be more likely.

In any event, I am not sufficiently conceited to think that my sun is the only one with a family of planets and, therefore, that our little earth is unique. Once we admit that the other stars probably also have planets, at any rate a goodly proportion of them, it is more than likely that a large fraction of these will be the right size to keep on their surface water and, possibly, an atmosphere of some sort; and, furthermore, at the proper distance from their parent sun, to maintain a suitable temperature.

Do they house living creatures, or even plants? The answer to this question may never be known. It is conceivable that one day, possibly even in the not very distant future, it may be possible to travel to the moon, or even to Venus or Mars. The moon is only some 200,000 miles away, so that at a speed of 300 miles an hour it would only take three or four weeks to reach it; in interplanetary travel, if it comes at all, we must certainly reckon with far higher speeds than this, so that the time to reach the moon might be a matter of days rather than weeks.

Venus and Mars are, of course, much farther away—some hundreds of times in fact—so that to reach them will probably be a matter of months at the very least, even if interplanetary travel proceeds at the rate of many thousands of miles an hour. Still, the possibility of one day exploring these planets cannot be excluded.

It is rash to set limits to the progress of science. A man who had maintained at Queen Victoria's Jubilee that within fifty years one would fly the Atlantic in a matter of hours would have risked being certified and locked up; yet we have seen this happen, and in the circumstances I am not prepared to rule out with any confidence the possibility one day of journeys through space in vessels carrying supplies of food and oxygen to the moon and the nearer planets.

But even so, our chance of exploring the hypothetical planets surrounding other stars is so remote as to be negligible. The nearest star is so far away that even light, which travels at a speed of 186,000 miles a second, would take some five years to get there and back. Whatever one may think about the prospects of interplanetary travel, any speed of this order is quite out of the question. Even at a million miles a minute it would take some sixty years to visit merely our immediate neighbor. A young man starting off, if all went well, would return an octogenarian, and the odds are that our nearest neighbor might well lack suitable planets to support any flora or fauna of interest.

The next stars are about twice as far away, the majority of the stars in our systems some thousands of times farther, so that any prospect of exploring them can be ruled out. But the Milky Way, our own private system of stars, enormous though it seems to us, containing as it does thousands of millions of suns, is but one unit among hundreds of thousands of other smaller so-called spiral nebulae rushing about in space. The nearest is several hundred thousand times as far away as the nearest star; the farthest which one has observed a thousand times farther. These distances are so gigantic that the possibility of ever discovering any detail about entities so far away need not be considered. Never will it be possible to ask a question and get a reply. If we could communicate by wireless, it would take a million years for the answer to come back. Even if the Pharaohs had been able to send out a message, we would by now only be able to receive an answer from the stars quite near the center of our own galaxy. To get a reply from one of the distant nebulae, the message would have to have been sent before the first man walked upon the surface of our globe.

When we see them, we only know what they were like hundreds of thousands, indeed millions, of years ago, but the answer to the question whether they contain numerous suns possessing planets, and whether any of these support life, will always remain an enigma. All we can say is that with hundreds of thousands of nebulae, each containing thousands of millions of suns, the odds are enormous that there must be immense numbers which possess planets whose circumstances would not render life impossible. If we are sufficiently self-centered and choose to deny that any of these support life, no one can prove we are wrong. But I, for one, am not so immensely impressed by the success we are making of our civilization here that I am prepared to think we are the only spot in this immense universe which contains living, thinking creatures, or that we are the highest type of mental and physical development which has ever appeared in the vast compass of space and time.

Preface

He established the Earth upon its foundations, that it falters not forever and ever. Psalm 104:5.

What is life? This matter is under argument and there are many proposed solutions for it. Most organisms live today in so called "normal" conditions that we consider ambient habitats. Others, mainly certain microorganisms, are extremophilic creatures and thrive in severe conditions (from our anthropological point of view) [0.111]. The cradle of Earth during primordial life is presumed to have been hellish for those first organisms exposed to the Hadean atmosphere then on Earth. Extant extremophiles include, for example, thermophilic Archaea and Bacteria that can live up to 115°C [0.109]. Some can live in various ranges of pH from 0, very acidic, to pH 14, very alkaline. Or consider the microbes living at the bottom of the deep ocean under very high pressures [0.92]. Microbial extremophilic representatives (prokaryotes and eukaryotes) have been found in hypersaline bodies (as in the Dead Sea, Israel and in the Great Salt Lake in Utah, USA) with up to a saturated concentration of salt [0.52]. There are other factors of stress and they can appear together in habitats containing "polyextremophiles" [0.110].

There are several theories about the origin of life in the Universe, but the source of initial life is still enigmatic. We have no real solution. Among the origin suggestions there are the prebiotic soup, warm or hot, and on the ocean floor where hyper-thermophiles living at hydrothermal vents [0.41] could have survived. The source for the origin of life has also been suggested from fumaroles, geysers, tides and hot springs [0.13] [0.29] [0.31] [0.32] [0.33] [0.118] [0.30]. There is also a theory that life began from gases and lightning [0.46] [0.95] and that then the amino acids that formed joined to become proteins and then a live protocell. There is an idea that the origin started from aerosol bubbles [0.78] [0.79]. Many presume that chemical evolution came before the first protocells, a key idea of the "RNA World". There is also the ancient hypothesis of panspermia [0.120] where life arrived at Earth from another celestial body. It is an open question: what is the source of life, extraterrestrial or on Earth? If life fills our Universe, it must have started independently many times [0.55].

Other opinions suggest a cold origin of life [0.44], as on comets [0.62]. Microbial life occurs in deep frozen areas such as permafrost or under the glaciers in Siberia, Arctic zones and Antarctica.

The literature on origin of life is huge, perhaps embarrassingly so for an unsolved problem. For instance, a Web of Science search on "origin of life" OR abiogenesis OR prebiotic (all fields) yields over 17,500 publications, and a corresponding Google Books search shows over 200 books with these words in their titles. Google Scholar shows over 380,000 publications. The discoveries of over 5000 exoplanets in the Milky Way [0.14] and one in another galaxy [0.39], the Search for ExtraTerrestrial Intelligence (SETI) [0.119], the possibility of life on Mars [0.7], and the plethora of organic matter [0.96] and water [0.100] in space, suggest we might not be alone, but we don't know yet.

Given the vastness of the effort, and the lack of a decisive theory of where, when [0.59], and how life originated, the best we can do is sample some of the recent ideas on the origin of life.

We have divided our authors' contributions into 5 parts.

1. Introduction to the Origin of Life Puzzle

We start with an historical document by Winston Churchill as a Forward, written before the great rush into the origin-of-life question [0.19] (for more history see [0.43]), and we commend his scientifically informed writing. It would perhaps benefit society if politicians worldwide had similar interest in and respect for science. Then in Chapter 1 we proceed with an up-to-date historical overview of origin of life research [0.68]. The question with 100 answers [0.121], "What is life?" is then raised and thoughtfully answered in Chapter 2 [0.102]. As no one has created life from scratch, it is necessary to wend one's way through the philosophical sides of the question and partial answers, and Chapter 3 covers circularities, paradoxes, and anthropic bias in current thinking [0.6].

The vesicle approach [0.13] [0.29] [0.31] [0.32] [0.33] [0.118] [0.30] illustrates some ambiguities in terminology, as in terms of geometry it may be considered as starting more top-down, providing containers for the origin of life, also top down historically rather than assuming that the protocell membranes came towards the end of the process, but depending on the process whether they are made, one by one in a microfluidic device they would be top-down, whereas if self-assembled – they would be bottom-up. For complex systems, there is the additional dilemma of which of many features came first, similar to the chicken or the egg? Chemistry first, or physics first? As the consensus is that the historical question of the origin of life is not unambiguously solvable, we use processes to distinguish bottom-up approaches starting from a small number of non-biological components, [0.66] [0.82], rather than top-down approaches starting with a living cell and engineering its genes and proteins down to a minimal cell [0.130].

2. Chemistry Approaches

The predominant view is that the origin of life is a problem in chemistry. This view is represented here by Chapter 4 tackling the origin of metabolism and the (protein-first) GADV hypothesis, based on 4 amino acids [0.65]. One approach of modelling by chemical automata in Chapter 5 presumes that a form of evolution could occur *en route* to life [0.12]. A chemical assembly theory of emergent information approach is taken in Chapter 6, and simultaneously applied in practice by a "chemputer" which makes experimental reactions automatically reproducible – a key ingredient to systematic experiments of chemical networks – that could potentially lead to life [0.23]. Considering early vesicles that could have formed from early amphiphiles from carbonaceous chondrite meteorites, research championed by David Deamer [0.13] [0.29] [0.31] [0.32] [0.33] [0.118] [0.30], their membranes were likely about half as thick as modern membranes. The transition to the latter is postulated in Chapter 7 to be in positive feedback via hydrophobic interactions with the PCR-like growth of peptides [0.53], possibly providing a model for one origin of proteins. Chapters

15 and 16 cover detailed experimental approaches to UV-driven chemistry that could have occurred both on the early Earth and on exoplanets. These cross-disciplinary questions are placed below with a set of chapters that ask when and where life started.

3. Physics Approaches
Physics approaches are rare [0.4] [0.22] [0.35] [0.47] [0.63] [0.72] [0.80] [0.88] [0.122], and usually involve phenomena at the cell size, such as bubbles [0.78] [0.79] or vesicles [0.13] [0.29] [0.30] [0.31] [0.32] [0.33] [0.118]. Here we provide valuable theoretical contributions and experimental attempts to tie previous information theories of life into potential theory-experimental approaches of minimal system requirements for chemical engineering of abiogenesis. The interdisciplinary approach of Chapter 6 above carries into physics by introducing metrics that try to quantify the complexity of single molecules, without needing the knowledge of how they were created. The persistence of mesoscopic states is related to the thermodynamics of life and its emergence in Chapter 8 [0.114] by describing the potential for developing system memory by memory-less processes. With the discovery of shaped droplets [0.36] [0.37], flat, polygonal oil droplets formed during slow cooling, rather than the expected spherical droplets, the exciting prospect was envisioned that these were an early step on the way to flat, polygonal Archaea, enhancing the Archaea First hypothesis [0.54]. This possible connection has been summarized here in Chapter 9 [0.49]. Again, crossing the boundaries of our parts, the plausibility of constructing non-biological devices that replicate themselves, imitating one characteristic of all life, is considered in Chapter 10 [0.64].

4. The Approach of Creating Life
Without a time reversal ability [0.107], we may never learn exactly how life formed. We can but guess and attempt to create life. If we are successful, then we will know at least one way life could have formed. The spectrum of *de novo* life approaches could be attempted both computationally [0.25] and by laboratory synthesis, [0.60] or as we've seen in Chapter 10, by artificial, evolving "robot-designers" as a step to self-reproducing robots, [0.64]. Thus we look into the possibility of synthesizing life bottom-up [0.66] [0.82], an approach that blurs at least some of the properties of nonliving and living systems (in Chapters 11 and 12) both for the creation of artificial organelles and on the road to artificial cells. The creation of viruses "from scratch" is yet to be achieved, as enzymes were used in synthesizing viruses [0.18], i.e., not "from scratch". Still, it is clear that a second origin of life, or even the creation of artificial viruses may prove to be dangerous to our life and demands forecasting their negative as well as positive consequences. Technological, ethical, and philosophical contributions are needed. Given the Viroid First [0.97] or Virus First [0.98] hypotheses, this might be a good place to start.

5. When and Where Did Life Start?
A recent fossil discovery [0.41] [0.67] may [0.125] extend our evidence for when life was established on Earth to just 237 million years after formation of the Moon via collision of Earth with another planet [0.5] [0.26] [0.48] [0.90] [0.103] (but cf. [0.3] [0.17] [0.38] [0.83] [0.91] [0.108] [0.115] [0.117]), as estimated in the Appendix to this Preface. While these fossils were found in a preserved sea vent, the number of day/night cycles from when the Earth cooled to allow water to condense to that time may be estimated as at least 305 billion

day/night cycles during those 237 million years (Preface Appendix, cf. [0.57]). In that time, living organisms could well have arisen elsewhere and been transported there by wind and/or currents (mixing time of the present, and presumable past ocean is at most between 1,100 and 1,500 years [0.94]) and adapted, as is probable with most extant organisms that thrive now at hydrothermal vents [0.40]. This problem of "local panspermia" (as compared to those from space [0.120]), usually called "invasive organisms", may always be with us. For example, after glaciation, most organisms in an area are invasive [0.113]. Here we can only add to the many plausible initial environments the sources of energy that is dissipated and that sustains life. Chapter 13 extends a new hypothesis of origin in nuclear geysers which is then commented on and presented with moderating viewpoints in Chapter 14 [0.69] [0.87]. The popular notion of life starting under sunlight, particularly high in UV due to lack of O_2 and O_3, is explored in much greater detail as to what exact chemistry could have happened. Chapter 15 connects recent computational and analytical advances on reactivity [0.124] under UV to decipher the possible precursor molecules to nucleosides and nucleotides on Early Earth. Chapter 16 in turn tests prebiotic chemical reaction networks that may arise on some of the thousands of known exoplanets, and proceeds to predict reaction intermediates and products given available UV conditions and rock minerals [0.105]. It is able to falsify several popularly assumed scenarios. Chapter 17 considers endoreic lakes (without outflows) [0.58], where moderate temperatures and hydrating/drying cycles drive abiogenesis - giving an alternative location to hot springs [0.13] [0.29] [0.30] [0.31] [0.32] [0.33] [0.118]. A challenge to the notion that the origin of life required concentrated energy sources is made in Chapter 17 [0.58].

Given the plethora of excellent ideas, we are faced with a dilemma [0.51]. Let us suppose there were *N* steps to the origin of life. Lacking a time machine, while we will never know *N* nor the order of the steps. The best we can do for now is to carry out those steps we reason happened, and try to create life from scratch. Suppose that for each step *i*, there are T_i theories that we have communally thought of. If only one theory were right, then the probability of choosing the right theory for that step is $p_i = 1/T_i$, unless we decide that some are more probable than others [0.15]. The probability *P* of choosing the correct sequence of theories is then the product of the p_i. The vast literature of tens of thousands of papers purporting to bear on the origin of life sometimes argue for some step being "First". If we think we know *N*, there could be up to *N!* ways of ordering the steps. We thus arrive at a worst-case analysis that:

$$P = (1/N!)\prod_{1}^{N}\frac{1}{T_i}$$

which could be a very small number.

For example, let us take just $N = 3$ as follows:

These have been deliberately alphabetized to not suggest favorites. To exemplify a meta-theory for abiogenesis, consider each idea for an event as *a priori* of equal probability, i.e., $p_1=1/T_1=1/25$, $p_2=1/T_2=1/14$, $p_3=1/T_3=1/15$. Their product is $P=p_1p_2p_3 = 0.000190$. But they might have occurred in 3! = 6 ways, reducing the *a priori* probability *P* of picking the right

1. Who's on First? [0.1]

1.1. Amyloid World
1.2. Archaea First
1.3. Aromatic World
1.4. Autocatalytic Anabolism
1.5. Bacteria First
1.6. Clay World
1.7. Coenzyme World
1.8. DNA World
1.9. Iron-Sulfur World
1.10. Lipid World
1.11. Mica/Biotite World
1.12. Nanoparticle-based World
1.13. Nucleoprotein World
1.14. Oligomer World
1.15. Protein/Metabolism First
1.16. Protein/Peptide World
1.17. Proto-tRNA Minihelix World
1.18. Ribonucleopeptide World
1.19. RNA World
1.20. RNA-Peptide/Protein World
1.21. Thiol-rich Peptide (TRP) World
1.22. Viroids-First
1.23. Virus World
1.24. World of Minerals
1.25. Zinc World

2. Where life started

2.1. Alkaline Vents
2.2. Endoreic Lakes
2.3. Hot Springs
2.4. Hot Volcanic Organic Streams
2.5. Hydrothermal Vents
2.6. Icy World
2.7. Interstellar Ices
2.8. Lava World
2.9. Nuclear Geyser
2.10. Ocean World
2.11. Panspermia
2.12. Salterns
2.13. Volcanic Aquifers
2.14. Volcanic Eruptions

3. Sources of chirality

3.1. Chiral Plasmas

3.2. Circularly polarized synchrotron radiation

3.3. Crystallisation

3.4. D-L-differences in some amino acids

3.5. Electron asymmetries

3.6. Far UV

3.7. Hypercycles

3.8. Interstellar dust

3.9. Liquid–liquid phase separation

3.10. Magnetic fields

3.11. Microvortices

3.12. Molecular Clouds

3.13. Neutrino Interactions with ^{14}N in Crossed Electric and Magnetic Fields

3.14. Self-replication

3.15. Weak interactions

theories in the right order to 0.0000317. Note that we have not used p_i=1/P_i, where P_i = the number of papers on an idea, eschewing consensus. We presume that N>>3. Given that the probability of getting back to the origin for a random walk in an N-dimensional space decreases rapidly with $N \geq 3$ [0.123], we likely need some good ideas on how to get from no life to life, or at least increase P for permutations of theories.

In memoriam, we would like to recognize the unique work on molecular imprinting of the late Paul Lauterbur, which we were unfortunately unable to include. RG met Paul Lauterbur (1928-2007) and visited his lab when he built the prototype MRI (Magnetic Resonance Imaging) scanner [0.74]. Paul was inspired by making an analogy between MRI signals and X-rays transmitted in what was then called "reconstruction from projections", now known as CT (computed tomography), using the ART (Algebraic Reconstruction Technique) algorithm [0.50]. At the time RG did not know of his other interest: origin of life, nor that after retirement RG would renew his interest in exobiology, now called astrobiology. Together they organized a session of a medical imaging workshop [0.56] and RG figured in his Paul's wife's biography of Paul [0.27] written after Paul shared a 2003 Nobel Prize for MRI [0.71] [0.77] and his death at 77 [0.101]. David Deamer recognized the importance of Paul's insights into the origin of life [0.34], as did Eric Drexler [0.42]. Paul had four publications on molecular imprinting [0.45] [0.70] [0.76] [0.75].

References in this Preface are indicated by [0.1] etc.

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