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The origin of life I: When and where did it begin?

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For decades most scientists assumed that life emerged billions of years ago in a "primordial soup" somewhere on the Earth's surface. Evidence is mounting, however, that life may have begun deep beneath the surface, perhaps near a volcanic ocean vent or even inside the hot crust itself. Since there are hints that life's history on Earth extends back through the phase of massive cosmic bombardment, it may be that life started on Mars and came here later, perhaps inside rocks ejected from the Red Planet by large impacts. The traffic of intact rocks between Mars and Earth is now an established fact, and experiments confirm that microbes could survive the rigours of the journey through space if cocooned within such material. Unfortunately, this planetary cross-contamination compromises astrobiologists' hope of finding a second genesis in the solar system.

Introduction

A pivotal event in the history of science took place in 1859 with the publication of Charles Darwin's seminal work *On the Origin of Species*. Darwin gave a convincing account of how the richness, complexity and diversity of life on Earth has emerged, over billions of years, from a simpler common ancestor, through the mechanism of random variation and selection. However, Darwin pointedly left

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out of account any explanation of how life got started in the first place. It has to be said that, 140 years later, the problem of the origin of life remains a deep and tantalising mystery. At its heart lies the puzzle of how nonliving chemicals can transform themselves into a truly living thing. Even the simplest bacterium is so immensely complex it strains credulity to imagine such an entity popping into existence solely as a result of the random shuffling of molecules. Yet clearly there must exist a pathway of physical processes that leads from simple chemicals to complex life; the challenge is to discover what this pathway is, and whether it is unique.

The problem of life's origin – or biogenesis – has profound ramifications for both science and philosophy. A great deal hinges on the answer. If life arose merely as a chemical fluke of stupendous improbability, then we shall be alone in the observable universe, and the entire subject of astrobiology is robbed of its central motivation. On the other hand, if life emerges more or less automatically wherever there are earthlike conditions, then the universe could be teeming with living organisms. A universe with bio-friendly laws, in which life, and perhaps consciousness, are expected and fundamental products of natural processes, is arguably more congenial for our contemplation than one in which life on Earth is merely an incidental chemical quirk in a vast cosmos of pervasive sterility. In short, the search for the origin of life is a search for ourselves – who we are and what our place is in the great cosmic scheme of things.

It is convenient to divide the problem of biogenesis into three linked questions: when, where and how? Paleobiologists are close to determining when life became established on Earth. Theories of where life started have recently undergone some dramatic changes. Indeed, it is by no means certain that life even began on Earth; it could for example have started on Mars and come to Earth later.

The question of *how* life began remains the least tractable, although there is no shortage of theories and some considerable quantity of experimental data. I shall address the three questions in turn. In this paper I consider when and where life started, and defer a discussion of how to paper II.

First, however, an important general point must be made. How do we know that life on Earth derives from a single originating event? Could the extraordinary variety of organisms on our planet be evidence for multiple episodes of biogenesis? The answer seems to be no. Biologists have found that all known life on Earth is interrelated. For example, organisms share a common chemical scheme, in which genetic information is stored in nucleic acids (DNA or RNA), proteins are used as enzymes and structural material, and are manufactured by little molecular factories called ribosmomes, and so on. Significantly, all life on Earth shares a common genetic code. A typical gene (a specific sequence of DNA base pairs) will be a set of instructions for the manufacture of a protein, written in a four-letter alphabet (DNA is made up of four different chemical bases). On the other hand, proteins are made out of chemical building blocks called amino acids, of which terrestrial life uses twenty different varieties. To make the right protein, the gene must instruct the ribosome to link together a specific sequence of different amino acids in exactly the right order to form a long chain. To translate the instructions from the DNA into "protein language" entails a mathematical code that maps 4 into 20. Life does this by batching the DNA bases into triplets, which can have $4^3 = 64$ combinations. That way there are enough permutations to specify each of the 20 amino acids, with some left over for stop commands and redundancy. (For a detailed review, see ref. 1.)

The fact that all terrestrial life uses the same chemical scheme and the same genetic code (with some very minor variations) strongly suggests that all known organisms have descended from a common ancestor in which these complex features were already established. The probability of a system of such extraordinary complexity and specificity arising independently along parallel evolutionary paths seems infinitesimal. Note, however, that I refer to "all known organisms". Although it is unlikely, it is not inconceivable that one day we shall discover life in an obscure niche on Earth that uses a different code or even a completely different chemical scheme. If so, these organisms might represent the descendants of a second, independent, genesis. I discuss some speculations along these lines in a later section.

It is important to realise that the last common ancestor of life on Earth is not necessarily the same as the first living thing. To understand this, it is helpful to use Darwin's metaphor of the tree of life, in which, from a simple originating "trunk," new species have arisen by branching and re-branching over time. Extant life is represented by the twiglets at the top of the tree. By tracing back from two extant organisms, their last common ancestor will be encountered at the point where the branches meet. Taking all life on Earth today, we can imagine following the myriad branches right back to a deep common branching point – the universal ancestor organism. But this branching point may not lie on the central trunk of the tree. There may have existed earlier branches of the tree of life that became dead ends, *i.e.* have no surviving descendants today (see Figure 1). Indeed, from the foregoing it will be clear that the universal ancestor must have already been an immensely complicated and sophisticated organism.

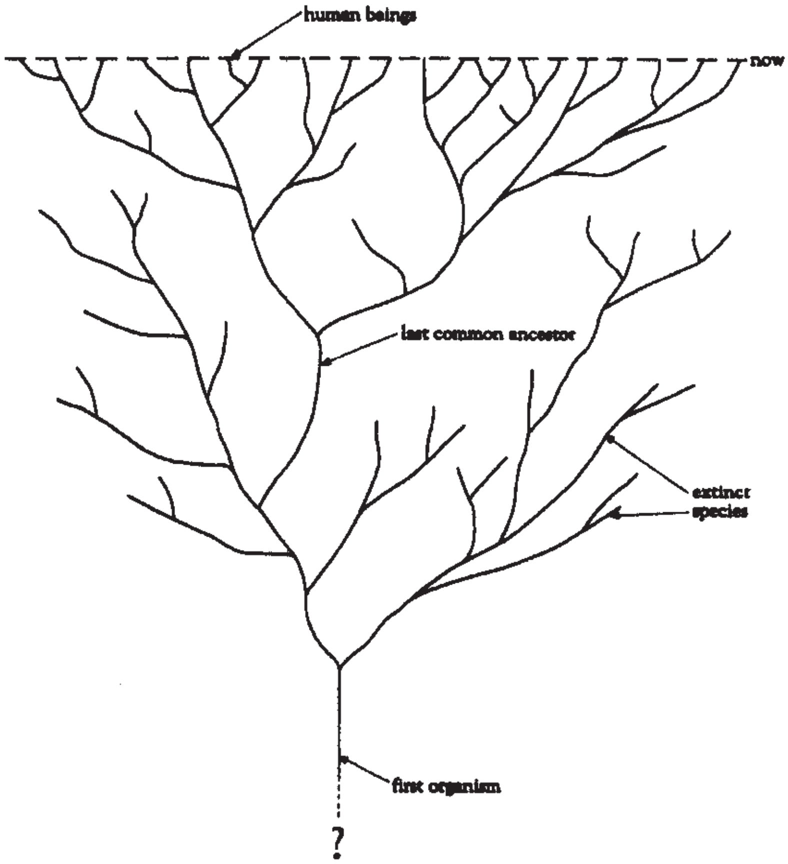

Fig. 1. *The tree of life, greatly simplified. The trunk of the tree represents the first living thing. The present day corresponds to the top branches of the tree, among which human beings are found. The universal ancestor of extant life is located at the last fork in the tree that connects to all the topmost branches. Branches below this fork correspond to organisms that have left no surviving descendants. The diagram as drawn greatly exaggerates the number of extant versus extinct species.*

There was surely a long period of prior evolution leading up to it. Pushing the tree analogy to the extreme, we can identify the origin of life with the single stem (or trunk, or root) from which all the subsequent branches sprang. Taking this literally implies that all life would have descended from a single microbial Adam. However, this interpretation is over-simplistic. Microbiologists know that genes can be transferred laterally between organisms, and this can blur the unique association of species with tree branches. In the ancient, primitive microbial realm, about which almost nothing is known, the tidy compartmentalisation into different competing species may have broken down. All we can really say with confidence is that all life on Earth has descended from a community of genetically promiscuous closely inter-related microbes.

When did life start on Earth?

By tracing back the fossil record, geologists can set a lower limit on the duration of terrestrial life. The oldest unambiguously identifiable fossil organisms are found in Western Australia, and date from about 3.5 billion years ago[2]. These were single-celled organisms resembling modern cyanobacteria, a photosynthesising microbe. Since photosynthesis is a complex process that must have taken some time to evolve, it is likely that life started some considerable time before. Unfortunately geological material much older than this is hard to find. In Greenland, sedimentary rocks with a minimum age of 3.85 billion years contain traces of carbon with altered isotope ratios that might be indicative of ancient biological activity[3]. If that interpretation is correct, it pushes back the epoch of terrestrial life to something approaching 4 billion years.

This early date for life on Earth has become something of a problem for astrobiologists. The solar system formed about 4.5 billion years ago from a swirling cloud of gas and dust. For about 700 million years the planets were pounded by debris as the primordial material aggregated into larger bodies. The record of this early heavy bombardment is conspicuous in the lunar cratering. Because Earth is larger than the moon, it would have taken many more big hits, but a combination of tectonic activity and erosion has obliterated all but the relatively recent impact craters. Even so, it is now recognised that bombardment of the Earth by asteroids and comets has continued throughout geological history and has also played and important role in shaping evolutionary history[4] (for example, by possibly destroying the dinosaurs).

Taking the lunar statistics as a guide, it has been estimated that Earth would have suffered dozens of impacts by bodies with diameters several hundred kilometres or more until about 3.8 billion years ago, when the ferocity of the bombardment began to abate. The effects of such major cataclysms have been studied by Sleep *et al.*[5] An impactor 500 km in diameter would strip away much of the atmosphere and replace it with a blanket of incandescent rock vapour at a temperature of 3,000°C. Swathing the planet, this global furnace would boil the oceans, creating a thick layer of superheated steam that would last for months before raining out. Hostile conditions would persist for about ten thousand years. The exposed surface of the Earth would be thoroughly sterilised, and a lethal heat pulse would travel about a kilometre into the Earth's crust.

If the Greenland results are to be believed, life's provenance on Earth extends back through the period of heavy bombardment, which raises the difficult question of how any living organism could have survived the global catastrophes of the larger impacts. One possible answer is that there were refuges in which life was protected from the worst effects. This leads naturally to the question of where life began.

Where did life begin?

First we must distinguish the location of the earliest established microbial colonies on Earth from the whereabouts of life's ultimate origin. Let me suppose for the moment that life started somewhere on Earth. Although Darwin was coy about the origin of life, he famously speculated in a letter to a friend[6] about a "warm little pond" in which all manner of chemical substances might accumulate over time. Then, driven by the energy of sunlight, ever more complex molecules might arise until a primitive life form accidentally emerged. This casual suggestion was later to form the model of the so-called "primordial soup," to which I shall return in paper II.

Given the mayhem caused by the cosmic bombardment, a warm little pond now seems a rather hazardous setting for elaborate, delicate and presumably time-consuming chemical processes to take place. In recent years many alternative locations have been proposed. The one that seems increasingly plausible and most consistent with Earth's violent early history is the deep subsurface.

In 1977 the submersible vessel *Alvin* discovered the existence of complex ecosystems kilometres deep on the floor of the Pacific Ocean, clustered around volcanic vents[7]. Some vents are termed black smokers on account of the dusky superheated fluids that spew from the seabed to form tall, blackened chimneys. The temperature of the emerging liquid can be as high as 350°C, but it does not boil on account of the immense pressure at that depth. Clustering around such vents are crabs and giant tube worms that have presumably invaded these niches from above, and adapted to the harsh conditions.

Because it is dark at these depths, photosynthesis is impossible, and the question arises of the energy source that sustains the ecosystems. The primary producers turn out to be microbes that inhabit the regions closest to the vents. They belong to the class of organisms known as chemotrophs, that exploit chemical and thermal energy rather than sunlight. Some chemotrophs are capable of turning minerals and gas directly into biomass. It came as a complete surprise that the hardiest of these microbes thrive in temperatures above 100°C. The official record is 113°C, although there are reports of still higher temperatures[8]. The name hyperthermophile is given to these extreme heat-loving microbes. Prior to the discovery of black smokers, the highest temperature life forms known were bacteria that inhabit hot surface springs, such as those in the Yellowstone National Park, typically at temperatures in the range 80–90°C. These were classified as "thermophiles." The fact that life can withstand temperatures in excess of the normal boiling point of water is remarkable. Indeed, many hyperthermophiles not only survive such torrid conditions, they actually require them to metabolise normally.

It turned out that black smokers were only the tip of a very large iceberg. The Ocean Drilling Programme has for some years been extracting rock cores from the seabed to depths approaching 1 km. These rock samples are also found to contain microbes in prolific abundance to the depth limit of the cores. For example, by counting using an optical microscope, Parkes has estimated microbial densities as high as 10^9 per cubic centimetre in some samples[9]. Because the temperature rises with depth, the organisms that inhabit the deep subsurface zone are either thermophiles or hyperthermophiles. At the time of writing, no clear limit to the habitable zone has been discerned, but presumably the combined effects of rising temperatures and decreasing rock pore sizes would prevent even small hyperthermophilic micro-organisms from living below a depth of about 5 km.

The abundance of subsurface life beneath the seabed is matched by similar discoveries on land. In the 1980s, Gold obtained evidence for living organisms at depths of several kilometres from an oil-drilling project through solid granite in Sweden. This work resulted in a trail-blazing paper[10] entitled "The Deep Hot Biosphere." Because of the sensational nature of the claim, however, Gold's work was greeted with much scepticism. But within a few years, other drilling projects, particularly in the Columbia River basin in the United States, have confirmed that live microbes are indeed found in abundance kilometres below ground[11]. Gold has estimated that if microbial life has extended across the planet in the subsurface zone, the total hidden biomass might rival that of surface life.

The existence of life far beneath the Earth's surface suggests the hypothesis that life began in a deep subsurface setting, where it would be afforded some protection from the heavy bombardment.

Organisms that dwelt more than a kilometre into the crust would have escaped the heat pulses from the rock vapour atmospheres created by even the biggest impactors in the period 4 – 3.8 billion years ago, so long as they were well away from ground zero. Because temperature increases with depth, and because the Earth's crust was hotter 4 billion years ago (the planets were still cooling from their formation), only hyperthermophilic organisms would have been candidates for inhabiting such refuges in the deep subsurface. Therefore, confirmation of this hypothesis would come if we could establish that the most ancient life was hyperthermophilic.

Fossil microbes from black smokers dated at 3.26 billion years have been discovered[12], but direct evidence of hyperthermophiles at earlier epochs is not yet forthcoming. There is, however, some highly compelling indirect evidence in the form of genetic sequencing. Techniques developed by Norman Pace and his co-workers[13,14] enable sequences of rRNA (ribosomal RNA) to be determined from field samples of organisms without the need to culture them in the laboratory (which is so far impossible for the vast majority of deep-living microbes). Consequently it has been possible to position the hyperthermophiles and thermophiles on the tree of life. The results[15] are shown in Figure 2. Here the lengths of the branches represent the genetic distances between organisms.

The first striking feature is that life is divided into three major kingdoms. The one termed *eucarya* consists of all multicellular organisms (including humans) and complex single-celled organisms with nuclei, such as the amoeba. The second kingdom incorporates the bacteria. The surprise is the third kingdom, *archaea*, consisting of microbes without nuclei that superficially resemble bacteria, but genetically are as different from them as they are from us. It is still unclear which of these kingdoms branched from which first, and exactly when those branchings occurred, but it is tempting to suppose that archaea came first, and then diversified into bacteria followed by eucarya.

Of more significance here are the bold lines in the diagram. These represent the hyperthermophiles. It is clear that they dominate all the lowest and deepest branches of the tree of life. Most of them are archaea. That means hyperthermophiles are in some sense the most ancient organisms on Earth today, having evolved the least over the past 3.5 billion years. We might think of them as living fossils. If this interpretation is correct, it implies that the earliest organisms on Earth were likely to have been hyperthermophiles, probably living deep in the hot crust, or clustered around black smokers in ancient oceans. This evidence therefore supports the hypothesis that the

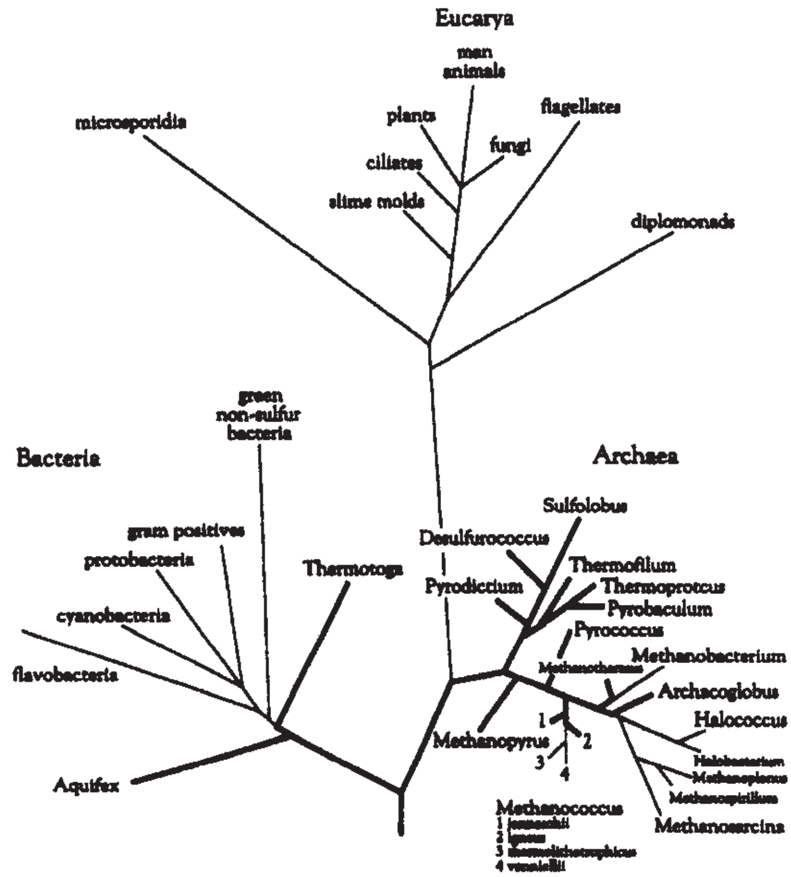

Fig. 2. *Living fossils. This portion of the tree of life depicts how far various species have separated genetically from each other. The lengths of the branches are proportional to the amount of genetic drift. The bold lines indicate heat-loving microbes (hyperthermophiles). Clearly the least evolved species, occupying the shortest and deepest branches of the tree, are all hyperthermophiles.*

earliest life dwelt in the relatively safe hot zone deep below the surface and came up only when the cosmic bombardment diminished.

Although there is circumstantial evidence that early life on Earth was located in the subsurface, we cannot be sure that life actually started there. It may have begun on the surface and migrated into the subsurface, adapting to the hotter conditions on the way. The next big impact would then have wiped out the surface and near-surface organisms, creating a genetic bottleneck through which only hyperthermophilic subsurface life squeezed. All life on Earth today might then be descended from these subsurface survivors, some progeny of which returned to the surface at a later, safer, stage. Indeed, if life emerges readily, it may be that it started many times on Earth during quiescent phases, only to be totally destroyed by subsequent impacts, again and again[5,15].

It is also not inconceivable that descendants of an earlier genesis than ours might have survived deep underground, yet to be discovered, or may even exist right under our noses, unrecognised for what they are. Intriguingly, there are claims[16] that ultra-small entities, variously termed nannobacteria or nanobes, might represent an exotic terrestrial life form. These are objects found in rocks[17] and even human blood[18], with a size of about 100 *nm*, about a tenth that of the smallest known bacteria. (This is comparable to the tiny features in the Martian meteorite ALH 84001, said by some NASA scientists to be fossilised microbes – see below.) At the time of writing, these claims remain highly controversial, not least because the objects appear to be too small to contain the minimal biochemical machinery to function as autonomous living cells.

The same big impacts that imperilled early life also blasted copious quantities of material into space. Much of the ejecta, in the form of rocky debris, would have gone into orbit around the sun. Some of the rocks would have returned to Earth eventually, perhaps after a sojourn of millions of years in space. It is possible that following a major impact cataclysm, with its attendant sterilising rock vapour atmosphere, terrestrial microbes inhabiting ejected rocks survived their time in space and were returned to Earth at a later stage, when conditions were more favourable. Thus outer space, as well as the deep subsurface, offers another possible refuge from the early bombardment.

At first sight, it seems unlikely that any life would survive being propelled off the surface of a planet and then being exposed to space conditions for an extended duration, but recent research has shown that the hazards are actually not too serious. The physics of impact ejection has been studied by Melosh[19]. The impactor itself mostly vaporises on contact with the surface. The explosion sends out a shock wave into the surrounding rock strata. The strata beneath the impact site are strongly compressed and shock heated to lethal temperatures, but on the periphery, the surface rock cannot be compressed (atmospheric pressure is negligible), and so the shock wave simply accelerates the material skywards, relatively uncompressed and unheated. The crater thus forms by excavation of unshocked or lightly shocked material. Microbes in the rock would therefore not be automatically killed by shock heating. Of course the impulse is still enormous, but experiments with centrifuges and artillery shells have shown that terrestrial microbes can easily withstand the accelerations needed to propel a rock into orbit[20]. Moreover, analysis of the Martian meteorite ALH84001 shows it was not shock-heated to lethal temperatures when displaced from Mars[21].

Once in space a microbe faces radiation hazards from solar ultraviolet, solar flares and cosmic rays. The vacuum and the cold of outer space do not present a problem; indeed, freeze-drying bacteria is an excellent way to preserve them. The deadliest hazard is ultraviolet radiation, but this is easily screened by a thin layer of material. Cocooned deep within a rock of some metres diameter, microbes would be safe from ultraviolet, solar flares and most background cosmic radiation. There would still be a danger from the highest energy cosmic rays, and from the radioactivity indigenous to the rock itself. Microbes do not metabolise under freeze-dried conditions, but go into a dormant state, in some cases forming tough spore-like structures, which are known to have extraordinary resilience and endurance powers. For example, it has recently been claimed that bacteria have remained viable having been entombed in salt crystals for as long as 250 million years[22]. Dormant bacteria cannot repair DNA damage, so their longevity is limited by the inevitable degradation due to residual radiation and thermal disruption of the nucleic acid structure. Melosh and his colleagues have studied the durability of some highly radiation resistant bacteria inside a rock in space, and assigned lifetimes of up to millions of years in the case of larger rocks[23].

If microbes can safely hitch a ride inside rocks ejected from Earth, it seems inevitable that some of this fecund material will have reached Mars with a cargo of viable terrestrial microbes. Since the journey time to Mars on a favourable orbit might be only months or years, microbes clearly have the survival capability of making the journey. Recent surveys of Mars have shown that it was warm and wet, and not unlike the Earth, before about 3.5 billion years ago. Mars has abundant water, and also many large volcanoes, opening up the prospect for hydrothermal systems there similar to black smokers[24]. If microbes from a hot subsurface setting on Earth were ejected by an impact and reached Mars, and then fell into an ocean near a volcanic vent, conditions would have seemed very much like home.

Because the bombardment was so intense at this early epoch, there would have been a prolific traffic of terrestrial material to Mars, a fraction of it laden with viable micro-organisms. Mileikowsky *et al.*[23] have estimated that at least 10^8 terrestrial rocks 1 m or more in diameter that avoided shock heating to > 100°C reached Mars during the early heavy bombardment phase. Some of this material would have burned up on entry into Mars' atmosphere, but a significant portion would have reached the surface unscathed. Over hundreds of millions of years it seems highly likely that transfers of viable organisms took place from ecosystems on Earth to similar ones on Mars. We must therefore conclude that Mars and Earth are not biologically isolated, and that cross-contamination of the two planets has occurred throughout history.

Did life come from Mars?

If Earth rocks can convey terrestrial microbes to Mars, can the reverse also happen? Could putative Martian organisms come to Earth inside Mars rocks ejected by impacts? There are currently 15 meteorites on Earth positively identified as of Martian origin. One of these, ALH 84001, found in Antarctica in 1984, was the subject of controversy when NASA scientists claimed to have identified fossilised micro-organisms inside[25]. Subsequent work has cast serious doubt on this claim. Nevertheless, the episode did serve to focus attention on the possibility that evidence for life on Mars, and perhaps even viable Martian microbes, might come here inside rocks ejected from Mars by large impacts.

It is more probable for Mars rocks to come to Earth than vice versa because the smaller surface gravity of Mars makes it easier for material to escape. Mileikowsky *et al.*[23] have estimated that 10^{12} tonnes of Martian material capable of transporting viable organisms have reached Earth in the last 4 billion years. It therefore seems likely that if ever there was life on Mars in the form of subsurface microbes dwelling within porous rocks, as is the case on Earth, then they will have been conveyed to Earth inside Martian ejecta. Computer modelling[26] of the orbital characteristics of ejected Mars rocks indicates that about 7.5 per cent eventually hit Earth, one-third within 10 million years – brief enough for hardy terrestrial microbes to survive space conditions. In any case, some fraction of this prolific traffic of rocks will reach Earth on a much shorter time scale. So if Martian organisms resemble terrestrial microbes, there is a good chance that some will have reached Earth still alive.

There is, of course, the final hazard of surviving the intense heating that would accompany high-speed entry into the Earth's atmosphere. Many meteorites burn up completely, but if the trajectory is suitable, they may reach the ground intact. Heating will ablate the surface, but the deceleration time is so short that little heat penetrates to the interior. Any micro-organisms deep within a meteorite would be unaffected.

The possibility therefore arises that life may have begun on Mars and come to Earth later. Mars was a more favourable planet for life in the early phase of the solar system. Being smaller than Earth, it cooled quicker, so the comfort zone for deep-living organisms was deeper sooner, providing an earlier refuge from the bombardment. Earth became safe for life only when the crust deeper than a kilometre cooled below about 120°C, enabling hyperthermophiles to take up residence far enough down to escape the sterilizing heat pulses from the big impacts. On Earth, these conditions may not have occurred until about 4.0 billion years ago, whereas Mars may have reached that stage as early as 4.3 billion years ago.

Another factor favouring Mars as an early abode for life is the lower degree of violence it suffered from impacts. In particular, Mars escaped the really huge impact that created the Earth's moon about 4.5 billion years ago. Being a smaller target, it also took fewer hits. Also, as pointed out by Sleep *et al.*[27], Mars lacked a global ocean, unlike Earth, so the sterilizing scenario of a superheated steam and rock vapour atmosphere enveloping the planet was less likely. Finally, because of the lower surface gravity of Mars, ejection into solar orbit is less violent, making it easier for microbes to escape to space as a refuge from the aftermath of big impacts, enabling Mars to be repeatedly recolonised, as fecund debris returned to the planet after conditions had improved.

For these various reasons, it may be that life got going on Mars, say, 4.3 billion years ago, and over a period of several hundred million years a steady rain of microbe-laden Martian debris fell on Earth. However, because of the uncongenial nature of our planet at that early time, these transferred organisms did not flourish, at least for long. But when conditions settled down, perhaps 3.9 billion years ago, widespread colonization would have been possible.

How likely is it then that we are all descended from Martians? The case is by no means a compelling one, since we have very little idea about the precise setting in which life originated. If it was a hydrothermal system, as I have hypothesized was the most likely, then Mars was probably the better planet. But whatever is the case, it now seems certain that Earth and Mars have been able to cross-contaminate each other. If for no other reason than it got there from Earth, there must have been life on Mars at some stage, even if it failed to thrive there for long. Because conditions on Mars resembled those on Earth at a time there was certainly life here (about 3.6 billion years ago), it seems probable that any terrestrial organisms reaching Mars alive during that planet's warm, wet phase would have been able to flourish, at least until the atmosphere thinned and the temperature plunged, after about 3.5 billion years ago.

Could there still be life on Mars? Today the surface of the planet is a frozen, desiccated desert bathed in ultra-violet radiation, with a very low atmospheric pressure and highly oxidising topsoil. Liquid water, though it clearly does flow on the surface from time to time, is likely to be found only deep underground, where volcanic heating may have melted the permafrost to create briny reservoirs. These could possibly harbour chemotrophic microbes of the sort that make a living deep inside the Earth's crust. However, this possibility remains something of a long shot.

If one day we do obtain unambiguous evidence for past, or even present, life on Mars – such as from the rocks brought back by the forthcoming sample return mission[28] – then it is likely that Martian life will turn out to be just a branch on the same tree of life as ourselves, either because life began on Mars and came to Earth, or vice versa. This would be a pity, because it would fail to answer the key question of whether life is simply a chemical fluke that has happened once, or an expected and automatic product of bio-friendly physical laws. Philosophically, the most exciting upshot of astrobiology would be the discovery of a second genesis, that is, another sample of life stemming from an independent origin.

The rocky transport of microbes between planets is important for near-neighbours, but could it propagate life farther afield? Europa, a moon of Jupiter, may have a global ocean of liquid water trapped beneath a crust of ice. Volcanic vents on the sea floor could create black smoker type conditions and thus provide a habitat for life. It is improbable (but not impossible) that Europa and Earth/Mars have contaminated each other, given the greater distances involved. So perhaps Europa offers the best hope within the solar system of finding a second genesis. When it comes to earthlike planets in other star systems, there is negligible chance of contamination by rocky transportation: the probability of a rock blasted off Earth ever hitting an earthlike planet in another star system is infinitesimal.

Before leaving this topic, however, mention must be made of the so-called panspermia hypothesis, formulated scientifically by Svante Aarhenius[29] almost a century ago, and revived in recent years by Fred Hoyle and Chandra Wickramasinghe[30]. The basic scenario is that individual microbes are small enough to be propelled across the galaxy at high speed under the effect of the pressure of light from the parent star. Arrhenius envisaged the galaxy seething with viable microbes journeying through space. When a microbe encounters a suitable planet, he supposed, it might colonize it. In this way life could arise from a unique genesis event, and subsequently spread across the entire universe. The location and manner of life's ultimate origin are sidestepped in the panspermia theory, so it is not so much a theory about the origin of life as about its dissemination.

Today we are more aware of the radiation risks of outer space, and it seems very unlikely to this author that a naked microbe, exposed to the ultraviolet of the sun and other forms of radiation, would survive for very long – certainly not for the millions of years needed to reach another star system. It is possible to imagine more complicated scenarios, for example, in which life takes refuge (or is incubated) within comets. Perhaps a life-bearing comet eventually becomes incorporated in the formation of a new planetary system, whereupon its microbial cargo is spewed forth into interplanetary space as the comet evaporates. But such astronomical Just-So stories require long chains of coincidence. Whilst it would be foolish to rule out the possibility that life might from time to time jump between nearby star systems due to a favourable concatenation of events, the case for a systematic spread of life through interstellar (let alone intergalactic) space by such mechanisms looks very shaky.

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