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Davies, P. C. W., (2005) The Search for life in the universe. *SPIE proceedings : Astrobiology and planetary missions*, 31 July - 2 August, 2005, San Diego, California. Bellingham, Washington : SPIE.

Access to the published version: <http://dx.doi.org/10.1117/12.624239>

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The search for life in the universe

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ABSTRACT

The existence of life places strong constraints on the cosmological initial conditions and the laws of physics. Cosmologists have long been intrigued by the “unreasonable” bio-friendliness of the universe in this regard. The explanation of choice is now the so-called multiverse cosmological model, which emerges naturally by combining the inflationary universe scenario with string theory. However, in the absence of an efficient panspermia mechanism, the question of whether or not life is *widespread* in the universe is not addressed by cosmology. Rather, it hinges on whether biogenesis is dominated by chance, or some elusive “life principle.” One way to test the fashionable, but as-yet unjustified, claim that life arises readily on earth-like planets is to seek evidence for multiple genesis events on Earth. I offer some proposals for experimental test.

Keywords: astrobiology, cosmological biophilicity, life principle, multiple geneses, bio-makers, chirality

1. THE UNREASONABLE BIO-FRIENDLINESS OF THE UNIVERSE

Most astrobiologists take the existence of life for granted. Many tacitly assume that the universe is intrinsically bio-friendly, and some even go so far as to articulate a sort of informal “life principle” – that the emergence of biological organisms somewhere in the universe is all but guaranteed, because life is somehow “written into the laws of nature.” However, these beliefs – though they may be correct – have no basis in known physics¹. Physics seems to be “life blind” – there is nothing in the known laws of physics to favor, or single out, the living state from any other state of matter. No known law of physics contains “life” as an end state or attractor, toward which matter and energy are destined to evolve. Thus, a priori, we have no reason to favor a universe rich with life over one in which life has arisen just once by a fluky combination of circumstances. This indifference of physics with respect to life makes the search for life in the universe a risky quest, for not only do we have no idea of the probability of life arising at any given site, we have no way even to reliably assign a probability to the probability! The only data point we have is that life emerged on Earth fairly soon after our planet became habitable, suggesting a probability for biogenesis not very close to zero². But that is about all. It is a slender philosophical basis on which to pin such a momentous and expensive search.

In spite of the fact that physics to date has no inbuilt life principle *sufficient* to guarantee life, it has many remarkable and unexpected *necessary* features, especially if we extend the definition of physics to encompass cosmology. It is now generally accepted that the universe started with a big bang. A searing explosion may seem an unpromising start for a universe destined to spawn life, but on closer examination the early universe seems to have been peculiarly bio-friendly in several respects³. The big bang was not just a chaotic, energetic outburst, but an exquisitely orchestrated affair. For example, had the explosive vigor been slightly greater, the cosmological material would have dispersed too rapidly for galaxies, stars, planets and – presumably – life to form. But had the bang been weaker, it would not have overcome the mutual gravitation of all the cosmic matter, and the universe would have collapsed back on itself to a big crunch before stars, and life, had time to form.

Cosmologists were for a long time puzzled by the coincidence that the vigor of the big bang was so precisely and felicitously matched to the gravitating power of the universe, but today they explain it by appealing to the so-called inflationary universe scenario. In this theory, the universe is postulated to have leapt in size by a factor of at least 10^{60} during the first 10^{-32} s, propelled by an intense pulse of antigravity that created a fleeting phase of exponential expansion. This inflationary phase automatically propelled the universe on the path of expansion at precisely the rate

needed to avoid a big crunch, yet slow enough to permit the local aggregation of matter to form galaxies. In other words, a life-encouraging universe turns out to be built into the basic cosmic dynamics.

A related fact is that, on a very large scale of size, matter is distributed extremely smoothly across the universe, which is important for life, because a universe that expanded rapidly in some regions or in some directions, and slowly in others, would be dangerously chaotic, leading to the disruption of galaxies by collisions. Inflation explains this uniformity, because inflation was democratic: it singled out no favored direction or cosmic region for special treatment. Thus any initial irregularities would have been rapidly smoothed away. On the other hand, had the post-inflationary universe possessed *exact* uniformity, matter would never have aggregated into galaxies and stars. Fortunately, the large-scale smoothness of the early universe was accompanied by (relatively speaking) small-scale irregularities – variations in the density of matter of about one part in 10^5 . These perturbations show up in the thermal map of the sky recently compiled by the satellite WMAP. The radiation imaged by WMAP has traveled almost undisturbed since about 380,000 years after the big bang, and is effectively a snapshot of what the universe was like at that time. Distinct hot and cold regions speckle the sky, betraying the slight variations in density and temperature. The significance of these variations is that they constitute the seeds of the large-scale structure of the universe. They were slowly amplified over time as the gravitational pull of the over-dense regions drew in more matter from their surroundings. Eventually the denser blobs evolved into clusters of galaxies.

From the point of view of life, the primordial irregularities revealed by WMAP are crucial. Had the variations been larger, the dense regions would have imploded to form supermassive black holes rather than galaxies. Conversely, weaker variations would have been inadequate to trigger the formation of galaxies. Either way, the existence of life depends on the primordial density perturbations having the right amplitude. The origin of these perturbations is not understood, but they are most likely the distended relics of quantum fluctuations dating from the inflationary era, writ large and frozen in the sky.

The early universe is just part of the story of cosmic bio-friendliness. The laws of physics quite generally seem to be cunningly contrived for life – “a put-up job,” to use the words of Fred Hoyle⁴. Hoyle was much struck by the fact that the formation of carbon, the life-giving element, inside stars is a very touch-and-go affair⁵. Carbon is made in a nuclear process that involves three helium nuclei coming together more or less simultaneously and fusing to make a single carbon nucleus. Without this reaction, the route to carbon, and elements beyond such as oxygen, would be blocked. On the face of it, the reaction rate for triple-helium fusion seems hopelessly small. Hoyle conjectured that the cross section must be amplified by a nuclear resonance in carbon at just the right energy for three helium nuclei, plus some thermal energy. Hoyle realized that this happy coincidence, without which life may never have existed, depends in turn on the strength of the force that binds nuclei together. Had the nuclear force been just a few per cent stronger or weaker, carbon would not have formed in abundance in the universe.

Since Hoyle’s observations in the 1950’s, many additional examples of the “fine tuning” of the laws of physics in relation to life have been uncovered⁶. For example, the dissemination of carbon in supernova explosions depends rather finely on the strength of the weak nuclear force, which controls the interaction of the imploding stellar material with the neutrinos emitted as the stellar core collapses. If the weak force were stronger, the neutrinos, which are responsible for dispersing the outer layers of the star into space, would remain trapped within the core. On the other hand, had the weak force been weaker, the neutrinos would not have gained sufficient purchase on the outer layers of the star to propel them into the interstellar void.

Examples like this have convinced physicists that the existence of life – at least, life as we know it – depends rather sensitively on both the cosmic initial conditions and the precise form of the laws of physics. One way to envisage this is to imagine “playing god” and attempting to construct a universe with the basic features we observe. Suppose this god could twiddle a knob and make the strong force stronger, or twiddle another knob and make all electrons heavier, and so on. A simple analysis reveals that more than very minor tinkering with the knobs would in all likelihood fatally compromise the universe’s ability to generate life.

Disagreement sets in, however, concerning the implications of this pervasive and seemingly-contrived bio-friendliness. Is it just luck that the laws of physics and cosmic initial conditions were right for life? Or is it evidence for an observer selection effect? An increasing number of cosmologists interpret cosmic bio-friendliness as evidence for a multiverse in

which the laws of physics are interpreted to be merely local by-laws, valid in our particular cosmic region, but different in others³. According to the multiverse theory, if we could take a god's-eye-view, our so-called universe would be seen as but a single "bubble" of space amid countless other bubbles – other "pocket universes" – and the big bang in which our cosmos originated would be accompanied by other big bangs in other parts, perhaps forming an unending sequence⁷. The multiverse is not just an idle speculation, but the natural outcome of attempts to understand the origin of the universe as a physical process. In particular, some form of multiverse seems to be the unavoidable outcome of combining the inflationary theory of the cosmic origin with fashionable ideas about the unification of physics, such as GUTs and string/M theory. According to the latter, there are at least 10^{500} different low-energy states, each producing different physical laws at low temperatures as the universe cools from the big bang, leading to a vast "landscape" of possibilities⁸. The vast majority of pocket universes populating this cosmic landscape will not possess low-energy physics consistent with life. But in rare cases there will arise a universe with the right combination of biophilic properties. Obviously the vast majority of bio-hostile universes will go unobserved, so it is then no surprise that we find ourselves living in a universe well suited to the formation of life.

2. OPTIMAL VERSUS MINIMAL BIOPHILICITY

The conclusion of the previous section is not so much that the universe is fine-tuned for life per se; rather, it is fine-tuned for the essential building blocks and environments that life requires. Such fine-tuning is a necessary, but by no means sufficient, condition for biogenesis. Thus the selection argument fails to distinguish between minimally biophilic universes, in which life is permitted but is only marginally possible, and optimally biophilic universes in which life flourishes because biogenesis occurs frequently, i.e. life forms from scratch repeatedly and easily. Rees has distinguished minimal from optimal biophilicity in relation to the known laws of physics³. For example, if the value of the dark energy in our region of the universe is a frozen accident, and the probability of any particular value is uniformly distributed in the physically allowed range, then we might expect the actually observed value in our region to be not far from the threshold value at which life is permitted. If the cosmological constant were found to be, say, one million times smaller than the maximum permitted value, that would be evidence against multiverse selection. But a second issue is that, given the necessary condition that the known laws of physics lie within the requisite range for biology to be possible, is that sufficient for life to form with high probability within, say, a Hubble volume? We could imagine a universe in which carbon and stable stars are abundant, but in which the emergence of life nevertheless required more. For example, it might require exceptional, fluky, physical conditions (such as the chance formation of some extremely unusual molecules). Alternatively it might require additional, yet-to-be-elucidated, laws or principles, possibly themselves requiring an element of fine-tuning. Following Shapiro⁹, I shall refer to this second distinct aspect of biophilicity as *biological determinism*. It is the assertion that life will be almost inevitable given Earth-like conditions. Many astrobiologists are either witting or unwitting biological determinists. Some, such as de Duve¹⁰, believe that biological determinism is built into normal chemistry, others, such as Kauffman¹¹, seek its origin in additional physical principles.

Conflation of necessary and sufficient conditions is common in discussions of astrobiology. For example, it is often claimed that because the building blocks of life (C, H, N, O, P, S and certain organic molecules) are common substances, widespread in the universe, so too will life be widespread in the universe. But this is just as fallacious as claiming that because silicon is a cosmically abundant element so laptop computers will be widespread in the universe. Another example concerns the existence of liquid water beyond Earth (e.g. on Europa). This is often cited as a good reason to expect life there, on the basis that on Earth life is found almost everywhere that liquid water exists. One might indeed have legitimate reasons for doubting that life exists where liquid water is absent (e.g. on the Moon). Certainly liquid water is *necessary* for life as we know it, but it is by no means sufficient. On Earth, aqueous habitats are invariably inhabited because the biosphere forms a contiguous system: life invades niches with liquid water, it does not emerge there *de novo*. So whilst the NASA mantra of "follow the water" makes sense when looking for extraterrestrial life, the mere existence of liquid water as such does little to raise expectations that life will actually be found. Similarly, the abundance of carbon and the ubiquity of long-lived stable stars imply a bio-friendly environment, but on their own they do not imply that life will actually form. To draw that stronger conclusion involves an additional assumption, i.e. biological determinism.

Stated informally, a life principle might go something like this. Consider a homogeneous medium of pre-biotic building blocks such as nucleotides and amino acids. Let the probability of assembling the simplest living organism solely from

random rearrangements of the building blocks in a unit mass of this medium in a duration $t \sim t_{\text{universe}}$ be P_1 . Let the actual probability for life to emerge be P_2 . Then the existence of a life principle implies $P_2 \gg P_1$. We may define the *amplification factor* as P_2/P_1 . As is well known⁹, random molecular shuffling alone is exceedingly unlikely to make even a simple microbe from a planet covered in primordial soup within the age of the universe. Hoyle¹² estimated P_1 at $\ll 10^{-40\ 000}$. By contrast, SETI proponents, who tacitly assume a life principle when assessing factors for the Drake equation, frequently assert that $P_2 \sim 1$ for a single Earth-like planet, implying a staggering amplification factor of $\gg 10^{40\ 000}$. Just what sort of physical principle would involve a number of this magnitude is hard to imagine. Two popular theories are (i) molecular evolution and (ii) self-organization. Theory (i) is really a redefinition of life. It asserts the existence of replication, variation and selection among a class of molecules of molecular weight is \ll the molecular weight of the simplest known living cell¹³. If small enough replicator molecules exist, they may form by chance with a probability ~ 1 in a suitable medium of modest extent. An unanswered question is then just how fine-tuned the laws of physics need to be to permit the existence and replicative efficacy of these hypothetical molecules. Since we do not know what these molecules are (or even whether they exist) further progress on this matter must await future developments. It is possible to imagine, however, that the laws of physics would have to be even more stringently fine-tuned for such molecules to work as efficient Darwinian units. Theory (ii) is more easily studied, as several mechanisms of self-organization have been discussed in the literature¹¹. However, as far as I know, there has been no study to determine how fine-tuned the efficacy of self-organization might be in relation to the laws of physics. It would be interesting to know, for example, whether elaborate and delicate metabolic cycles such as the citric acid cycle are sensitive to the mass of the electron or the value of the fine structure constant. Theories (i) and (ii) do not exhaust the possibilities for attaining a large amplification factor. There may exist, (iii) new principles of complexity that will one day emerge from the general study of complex systems.

In the foregoing I have dwelt on theoretical considerations. It is possible, however, that the matter of minimal versus optimal biophilicity in relation to biological determinism will be settled by observation. This would be the case if a second, independent, genesis of life were found on, say, Mars or Europa – or, indeed, on Earth (see section 5). Unless it could be demonstrated that our solar system as a whole offered exceptional conditions, it would then be reasonable to assert that life is widespread throughout the universe, and would arise with a high probability on most earth-like planets. Before this conclusion is secure, however, we must confront the problem that there are two quite distinct ways in which life might be widespread in the universe. One is that the laws of nature and the cosmological initial conditions favor biological determinism and a life principle. The second is that life spreads efficiently across space – the so-called panspermia theory^{14, 15}. In the latter case, life may have started at just one location by an exceedingly improbable accident, but subsequently spread, establishing itself on a galactic or even cosmological scale during the multi-billion year history of the universe.

3. PANSPERMIA AND TRANSPERMIA

The theory that life has been transported between planets was championed by Svante Arrhenius a century ago. Arrhenius¹⁴ envisaged microbes high in the atmosphere of a planet being propelled by the pressure of starlight until they reached velocities sufficient to escape from their planetary system altogether. If this were to happen in large enough numbers, there is a chance that a fraction of such expelled microbes might encounter a sterile but congenial planet elsewhere and “seed” it with life. The panspermia theory makes no attempt to confront the problem of the ultimate origin of life; it merely shunts it off to “elsewhere”. There is no reason why panspermia cannot be combined with the assumption of multiple geneses of life, but the main attraction of the theory is that it permits the universe to be teeming with life even if biogenesis were a unique event.

Panspermia has attracted few supporters in recent years, with the notable exception of Hoyle and Wickramasinghe¹⁵. The main objection to the original theory is that the radiation environment of space is lethal to almost all known organisms. Hazards include solar and stellar ultraviolet, solar and stellar flares and cosmic radiation. Although examples of remarkable radiation resilience have been reported among certain terrestrial microbe species under special conditions^{16, 17}, it remains true that all known organisms would die quickly if exposed to direct solar ultraviolet, and more slowly (but still rapidly compared with interstellar transit times of millions of years) from cosmic radiation. It is possible to concoct elaborate scenarios in which microbes ejected from a planet are afforded a measure of protection from radiation (e.g. by coating in dust, immersion in an interstellar cloud or comet), enabling them to survive long enough to reach another star system, but such rare concatenations of events would not serve to provide a common

dissemination mechanism to populate the galaxy, let alone to permit transits across intergalactic space. So whilst it may be the case that, here and there, one planet has seeded another in a neighboring star system, pervasive panspermia propagation seems highly implausible.

The foregoing objections are largely circumvented, however, in a different scenario known as transpermia. In this theory, microbes are transported between planets cocooned inside rocks, which offer a measure of radiation and thermal protection^{1, 17-21}. Impacts by comets and asteroids with rocky planets are known to displace large masses of material. Theoretical studies by Mileikowsky et al.²¹ indicate that a substantial fraction of rocky ejecta would be displaced into orbit around the sun or parent star without suffering lethal shock heating. Some of these displaced rocks will eventually strike other planets and could thereby colonize them. This is an old theory; its essential elements were articulated by Kelvin as long ago as 1871. Transpermia would be a very efficient mechanism for transporting life between Mars and Earth, and to a lesser extent vice versa. Computations by Gladman et al.²² show that 7.5% of Mars ejecta will hit Earth eventually. Most microbes could withstand the *g* forces associated with impact ejection. The vacuum conditions and low temperatures of outer space need not prove lethal, as freeze-drying bacteria and archaea can actually increase their longevity. High-speed atmospheric entry would present a potential hazard of incineration, but rocks entering Earth's atmosphere at shallow angles would not invariably vaporize; fragments could reach the ground intact, and with short enough atmospheric transit times to prevent heat penetration to the interior. Mileikowsky et al. have studied the radiation and thermal damage hazards to dormant bacteria and spores in this scenario, and determined that viability times of the order of millions of years are not unreasonable²¹. This is easily long enough for live bacteria to make the journey from Mars to Earth.

The foregoing considerations make it almost inevitable that Mars and Earth will have cross-contaminated each other repeatedly during solar system history. Mileikowsky et al. estimate a traffic of about 4 billion tonnes of unshocked Martian material unheated above 100°C reaching Earth over the last 4 Gyr, and a smaller but significant amount going the other way²¹. Given that Mars was warm and wet at a time when life is known to have existed on Earth, the seeding of Mars by terrestrial organisms seems very likely. The reverse is also true. In fact, a good case can be made that Mars was a more favorable planet than Earth for life to get started, raising the possibility that terrestrial life began on Mars, say 4.4 billion years ago, and spread to Earth subsequently^{1, 23, 24}. Crucially, the possibility of transpermia seriously compromises the chances of finding a second genesis of life on our nearest neighbor planet. If traces of life are found on Mars it seems very likely that it would represent a branch of Earth life rather than an independent origin.

The probability of contamination by Earth (and Mars) rocks diminishes sharply with distance, so there is a good chance that Europa is free of this problem. Transpermia would be a very inefficient mechanism to propagate life between star systems, as the probability that a rock ejected from Earth or Mars by an impact will hit an Earth-like planet in another star system are negligible²⁵. The conclusion is that if biogenesis were a unique event, we might expect life to have spread beyond its point of origin to near-neighbor planets, but no further. If evidence for life were found outside the solar system (e.g. by detecting ozone in the atmospheres of extra-solar planets) it would provide strong support for biological determinism, with its implication of optimal biophilicity.

4. BIOLOGICAL DETERMINISM

I have argued that life will not be widespread in the universe unless fine-tuning is augmented by the assumption of biological determinism. Attitudes to biological determinism fall into three categories: (A) it is false; life is a fluke restricted to Earth (or near neighbors); (B) it is true, and it follows as a consequence of known physics and chemistry; (C) it is true, but is not implied by known physics and chemistry alone; additional discoveries or principles are needed, perhaps to be found in the emerging sciences of complexity and information theory.

Position A was supported most notably by Monod²⁶. Position B was adopted explicitly by Fox²⁷, who claimed evidence that the basic laws of physics and chemistry were biased in favor of producing biologically significant molecules. More recently de Duve has argued that whilst chemistry is not exactly slanted toward "life" in quite such an explicit manner, nevertheless biogenesis must be an expected product of chemistry¹⁰. Position C finds support from Eigen²⁸ and Kauffman¹¹. Evidence for B comes from pre-biotic chemistry, following the trailblazing experiment of Miller and Urey²⁹. The assumption has been made by many that the Miller–Urey experiment represents the first step on the road to life down which a chemical mixture would be inexorably conveyed by the passage of time. The common belief that

“more of the same” would eventually produce life from non-life can be criticized, however, as stemming from a 19th-century view of the living cell as some sort of “magic matter” that can be cooked up in the laboratory by following an appropriate recipe; in other words, that biogenesis is primarily a problem of chemistry and chemical complexity.

An alternative view of life is that the cell is not so much magic matter as supercomputer – a digital information processing and replicating system of enormous fidelity. Defining life through its informational properties rather than its chemical basis is akin to focusing on the software as opposed to the hardware. In general there are two aspects to biogenesis: the formation of an appropriate chemical substrate, and the emergence of an information-processing system. A fully satisfactory account requires an explanation for both hardware and software. So far, most of the research effort has been directed at the former. But according to the informational view of life, the nature of the hardware is secondary, since the essential information processing need not demand nucleic acids and proteins; it could be instantiated in alternative chemistry (such as in the clay crystal proposal of Cairns-Smith³⁰) or physics. For example, the study of quantum computation and quantum information processing is elucidating the rules of quantum replication. The quantum no-cloning theorem forbids the flawless replication of a quantum state³¹ (a fact implicit in Wigner’s famous paper supposedly proving a conflict between life and quantum mechanics³²). But it is not the wave function we want to replicate; it is information. Life may have started as a system that copied qubits, maybe not in one step but in a series, and quantum fluctuations provided the necessary variations for some sort of quantum Darwinism to get under way. So maybe there is a life principle built into quantum mechanics combined with environmental selection³³.

In conventional molecular evolution (i.e. molecular Darwinism), which falls under category C, the laws of physics and chemistry are augmented by the principle of natural selection, which enables information to be shunted from the environment into the cell. This may (or may not – we lack any proof) be sufficient to yield a form of biological determinism, especially if the phenomenon of convergent evolution was as manifest in molecular evolution as it is in normal Darwinian evolution³⁴. Of course, this begs the question of why “life as we know it” conveniently constitutes an attractor in the vast space of molecular complexity. It also raises the question of whether such canalized chemical pathways are sensitive to “fine-tuning” of the laws of physics, and if so by how much. Although molecular evolution might account for the manner in which information can accumulate in a molecular system once a mechanism exists for information processing, replicating and storing, it fails to account for the origin of the information processing system itself. In other words, it offers a plausible account of the origin of the genetic database of early organisms, but not of the operating system *itself* at work in the cell. This is the same sort of distinction familiar from everyday computing: the database might be a list of addresses, for example, and the operating system Windows XP. The database of addresses is useless without the Windows operating system to access and process it. In the same way, genetic information stored on a genome is of no use on its own; it must be both interpreted and processed. Interpretation requires the operation of the genetic code, while data processing requires a suite of proteins and other specialized molecules to implement the instructions in life’s “program”. It is far from clear that molecular evolution proceeding by purely Darwinian means of random variation and selection can create these essential operating system features from scratch.

5. FINDING A SECOND GENESIS ON EARTH

As I have explained, biological determinism is a popular position among contemporary astrobiologists. That is to say, they believe that life will emerge with high probability on earth-like planets, although opinions differ on just how like Earth an “earth-like” planet needs to be. However, one planet known to be one hundred per cent earth-like is Earth itself. If life originated on Earth, rather than being brought here from somewhere else, the question then arises whether life may have arisen here more than once. If that were the case, it is of interest to ask what sort of evidence may exist for a second genesis of life³⁵.

One popular scenario places life’s terrestrial origin in a watery setting on or just below Earth’s surface, during the period of heavy bombardment between 4.0 and 3.8 Gyr ago. Because the largest impacts are likely to have thoroughly heat-sterilized the planet, one may envisage a series of “stop-go experiments” in which life emerges in a quiescent period after a large impact, only to be annihilated by the next large impact. As stressed by Maher and Stevenson³⁶, this process may have been repeated many times before life as we know it managed to squeeze through the environmental bottlenecks created by the remaining large impacts to survive to the present.

Very little is known about the expected duration, or the physical and chemical circumstances, needed for life to emerge on an earth-like planet. Estimates of the timescale range from a few million years^{37, 38} to billions of years, or even much longer³⁹. We do, however, have one crucial bit of information. Life established itself on Earth fairly quickly once conditions permitted. This is often cited as evidence in favour of the hypothesis that life arises easily and often. Lineweaver and Davis² used the observational constraints on the rapidity of biogenesis on Earth to conclude that on earth-like planets older than about 1 Gyr the probability of biogenesis is > 13% at the 95% confidence level. However, these results can equally well be applied to the Earth during the epoch of impact frustration³⁵.

If life began on Earth more than once, the question arises of whether there remains any record of life-as-we-don't-know-it (which for brevity I shall refer to as "alien life"). Four hypotheses may then be considered. (i) Life began more than once, but all samples of alien life were destroyed early on either by impacts or by other environmental insults, or in competition with "our" form of life. (ii) At least one sample of early alien life survived to co-exist for an extended period with familiar life, perhaps affecting its evolutionary history in some manner. (iii) Early alien life is extant, but has either gone unrecognized or is undiscovered. (iv) Alien forms of life have continued to arise (or be delivered to) Earth throughout evolutionary history, and may still be forming/arriving today.

If (i) were the case, direct evidence for multiple geneses would be very difficult to obtain. The terrestrial record of early life on Earth has been largely obliterated by impacts, tectonic activity and erosion. In principle, rocks from early Earth could be recovered from the moon or Mars, and may preserve traces of alien terrestrial life and/or familiar life. Hypotheses (ii) and (iii) imply that alien life was able to survive the bombardment. Is this realistic? Two possibilities suggest themselves. The first is subsurface refugia. If microbes dwelt more than ~ 1 km below ground, they may have survived even the largest impacts, so long as they were located far enough away from ground zero. The second possibility is that material ejected from Earth by impacts could serve to cocoon and preserve a fraction of the micro-organisms embedded therein. Some of this material will go into solar orbit and a fraction of that will be returned to Earth after the surface conditions have returned to normal. A variant on this second possibility is that some ejected material will eventually hit other planets. During the first Gyr of solar system history Mars, and possibly Venus (Grinspoon⁴⁰), offered a favourable environment for life. Terrestrial organisms might then have colonized, say, Mars (or vice versa), and earth life might then return later in Mars ejecta.

Hypothesis (iv) is often discounted using the reasoning that once life had become established on Earth it expropriated all the raw materials required to generate life *de novo* a second time (Darwin⁴¹). However, microbial life may not have been 100% efficient in consuming available resources. The objection also ignores the possibility of "genetic takeover" – that life might originate with one chemical system, and then evolve to adopt another³⁰. It might even be possible to observe some form of biogenesis at work in nature today, if the incubating environment were sufficiently undisturbed by the activities of familiar life. Finally, if different forms of life can arise in different physical and chemical environments, then even exhausting the resources of one form of life would not necessarily preclude the emergence of another form.

Another objection to hypothesis (iv) is that peaceful co-existence of life forms that compete for resources is intrinsically unstable. But this argument is clearly false for life as we know it. For example, bacteria and archaea occupy similar ecological niches, and are very different forms of life. Yet they have co-existed for at least 2 Gyr. A more serious objection is that biogenesis involving organic synthesis almost certainly required reducing conditions. The build-up of free oxygen through oxygenic photosynthesis, even at relatively low levels, would have inhibited further organic synthesis. The accumulation of atmospheric oxygen was a slow process, however, and would have been unlikely to accumulate to a level that would interfere with organic synthesis before about 3 Gyr^{43, 44}.

For all these reasons it is entirely conceivable that more than one form of life could have arisen and even co-existed on Earth. The question then arises of how we might identify a second sample of life in a terrestrial setting. The fact that we don't notice any alien organisms around us is in no sense fatal to the argument. Alien life would probably be restricted to microbes. Microbiologists and biochemists have devised a suite of tools customised for studying life as we know it; any alien microbes are likely to simply be missed or discarded in even the most general microbiological analyses involving bio-prospecting⁴⁵. Alien microbes might inhabit niches beyond the reach of familiar life, i.e. in locations as yet poorly explored by microbiologists. Or they may display literally alien properties that do not identify them as living organisms. Finally, they may be dormant and inactive, awaiting physical conditions very different from those associated

with familiar life. For all these reasons we could be surrounded by living, dormant or dead alien microbes without being aware of it.

How might we seek evidence for alien life on Earth? Several possibilities come to mind.

Geological bio-markers

The importance of life in shaping the Earth's atmosphere and lithosphere is well known, e.g. the release of oxygen in the atmosphere and the biogenic production of mineral deposits. Alien life might transform the geological, atmospheric and marine environments in novel ways that are unaccountable by conventional biological or abiological processes. One example might be the detection of opposite chirality biomarkers, non-racemic mixtures of biological material or anomalous ratios of stable isotopes that cannot be explained by abiotic or normal biotic processes. An important example of how fossil biomarkers can be used to trace the early history of life has been given by Brocks et. al.⁴⁶.

Novel environments

Alien life might occupy environments lethal to familiar life. A search of extreme natural or even artificial environments might uncover unexpected life forms. Such environments include deep ocean hydrothermal vents where the water temperature exceeds the upper limit for familiar life. Precisely what this upper limit might be is the subject of some debate, but somewhere approaching 130°C seems reasonable. Other possibilities are the high atmosphere⁴⁷, the very deep subsurface⁴⁸, grossly contaminated rivers, aquifers and lakes⁴⁹, and very low temperature locations⁵⁰. Assuming that even alien life requires liquid water, some mechanism for local heating (e.g. rocks buried in ice and heated by the sun) is necessary if extant life is being sought.

Genetic fossils

It is possible that remnants of alternative biochemical systems have become incorporated in extant organisms. For example, "alien" but innocuous genes might long ago have been laterally transferred and replicated⁵¹. Studies of ancient gene duplications may be able to identify such genetic anomalies⁵².

Biological filters

If alien life flourishes in more or less the same environments as familiar life, then looking in novel environments is unnecessary. Rather, we need to devise a means to separate familiar microbes from alien microbes. Any physical characteristic might differentiate between them. The problem of simply plucking an alien microbe from a general biological setting is daunting however. Very few familiar microbes, let alone alien microbes, can be cultured. An alien microbe might look superficially like a familiar bacterium; only a genetic analysis would disclose its exotic nature. The primer sets that are currently being used in bio-prospecting could be generalized⁵³. A technique to identify non-DNA organisms is to apply DNA stains and then use flow cytometry to selectively remove DNA-based cells. Any remaining cells could then be scrutinized microscopically and biochemically. If alien microbes were DNA based but non-ribosomal, they might be identified by fluorescent in situ hybridization probes (FISH) and separated using flow cytometry.

A more straightforward possibility concerns chirality. The origin of biological chirality remains contentious⁵⁴, but a plausible hypothesis is that it represents a frozen accident: early life broke the symmetry at random, producing the observed chirality with 50% probability. It follows that there is a 50% chance that a second genesis (or similar life) would select the opposite chirality. This would help peaceful co-existence. It would also provide a good way to detect alien life. If a nutrient broth with opposite chirality contents ("anti-soup") were used as a culture medium, familiar life might be unable to grow, but oppositely-chiral alien life may still flourish. Experiments with anti-soup have been performed on the sterile soils of the Atacama desert⁵⁵, and similar techniques are currently being tried by Richard Hoover at the Marshal Space Flight Centre on various extremophiles. Amino acids with opposite chirality occur naturally. Their origin is usually attributed to the racemization of decaying organisms^{56, 57}. However, it is conceivable that some of this material arises from the decay products of anti-chiral alien life. Experiments with suites of amino acids

and any reversed-chirality organic molecules found in association with them might provide convincing bio-markers for past anti-chiral life, especially if such life used a different set of amino acids from familiar life.

As a final example, if a means could be found to interrupt genetic machinery employing the universal genetic code, then any remaining signs of metabolism is likely to be either alien, or at least totally novel organisms. Other mechanisms can be envisaged that target ribosome function, or replicase enzymes. The alien life might then be identified by its metabolic products, or through labelled release experiments similar to the Viking procedures, or directly from microscopic searches and gene sequencing.

6. ROUTES TO LIFE

Given our ignorance surrounding the process of biogenesis, we may identify several possible scenarios that involve some form of multiple genesis.

1. Life starts from non-life more than once and each sample retains distinct physical and/or biochemical signatures throughout. Using the tree of life analogy, we would be dealing with multiple trees – perhaps a forest – rather than multiple branches sprouting from a common trunk.
2. As in scenario 1, but the *same* life emerges, either from scratch or via convergent evolution, perhaps to swap genetic or chemical material, or even to merge into a common biosphere.
3. Life starts from a single origin but evolves into such radically divergent forms that they might be classified today as different forms of life. Viruses might constitute an example⁵³.
4. Any combination of the above.

The problem we face is to retrodict from the present state of affairs. The universal biochemical system and shared genetic code are often cited as examples of a common ancestor, but it is conceivable, though admittedly highly unlikely, that these features resulted from convergent evolution from multiple origins. For example, there is evidence that the genetic code is near-optimal, and probably evolved from a less efficient precursor code⁵⁴. The same selective pressures might conceivably have generated the same code more than once.

Conversely, there is the problem of just how different must two samples of life be for us to be sure they descended from distinct origination events. Different genetic codes might suggest independent origins, but this need not be so. If the known code evolved from an earlier, simpler code, we cannot rule out an evolutionary bifurcation in the code in the distant past, producing distinct near-optimal codes today. Organisms with opposite chirality in their basic biochemistry would be stronger evidence for a second genesis, although one would need to rule out the possibility of an achiral precursor form of life that bifurcated into left- and right-handed versions. It is hard to see, however, that life could be based entirely on achiral molecules, so the mirror life experiments remain the most hopeful.

More radical alternatives are to consider forms of life that don't use ribosomes to manufacture proteins, or perhaps don't use proteins and/or nucleic acids at all, but employ a very different chemistry. It is easy to extrapolate progressively farther away from familiar life until a point is reached at which a common origin would seem implausible. However, this exercise in extrapolation does force us to confront the definition of life. In the foregoing I have tacitly adopted a rough-and-ready working definition along the following lines: Life is a carbon-based complex organized system that replicates information, maintains a far-from-thermodynamic-equilibrium state by exploiting some form of chemical metabolism, and is capable of evolving by variation and selection. But this broad definition fails to distinguish between two different possibilities for its origin. The first is that life emerged from non-life abruptly, rather like a phase transition. An analogy might be a gas that bursts into flame at a critical temperature, or a solute that crystallizes. If life began in this way as a discrete threshold phenomenon, it then makes good sense to discuss multiple origins, just as one may envisage bush fires starting independently at different locations. The second possibility is that there is no well-defined threshold at which a complex chemical system "comes alive." Rather, there is a continuous transition from a chemical mixture to autocatalytic cycles to something resembling a living cell. In this case, if all life emerged from

similar molecular evolution, one might still speak of a common (molecular) origin. But even in this case one would be justified in talking about multiple origins if the genesis events took place in, say, different windows between totally sterilizing impacts, or on different planets. In the foregoing I have not sought to discriminate between these various alternatives of multiple origins, but a more refined treatment might identify ways in which a slow continuous transition from non-life to life might leave a distinctive geological or biochemical record of the transition phase. It is also possible that such transitional forms might be found on extraterrestrial bodies, such as Mars or the moons of the giant planets, especially Titan.

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