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Hypothesis Paper

Finding a Second Sample of Life on Earth

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ABSTRACT

If life emerges readily under Earth-like conditions, the possibility arises of multiple terrestrial genesis events. We seek to quantify the probability of this scenario using estimates of the Archean bombardment rate and the fact that life established itself fairly rapidly on Earth once conditions became favorable. We find a significant likelihood that at least one more sample of life, referred to here as alien life, may have emerged on Earth, and could have coexisted with known life. Indeed, it is difficult to rule out the possibility of extant alien life. We offer some suggestions for how an alternative sample of life might be detected. Key Words: Origin of life—Biogenesis—Impact frustration. Astrobiology 5, 154–163.

SCENARIOS FOR A SECOND GENESIS

THE VIEW THAT LIFE WILL EMERGE with high probability on Earth-like planets is shared by many scientists, although opinions differ on just how like Earth an Earth-like planet needs to be (de Duve, 1995). One planet known to be 100% Earth-like is Earth itself. If life originated on Earth, rather than being brought here from somewhere else, the question then arises as to whether life may have arisen more than once. If that is the case, then it is of interest to ask what evidence might exist for such a second genesis of life.

A popular scenario attributes life's terrestrial origin to molecular evolution on or just below Earth's surface about 4 Gyr ago, during the period of heavy bombardment. Because the largest impacts were likely to have heat-sterilized the planet, one may envisage a series of "stop–go experiments" in which life emerged in a quiescent period after large impacts, only to be annihilated by the next large impact. This process may have been repeated many times before known life squeezed through the environmental bottlenecks created by the remaining large impacts (3.9–3.8 Gyr ago), and survived to the present day (Maher and Stevenson, 1988).

The possibility of multiple epochs of biogenesis is also consistent with an alternative scenario in which life began beyond Earth and was delivered by either a panspermia or transpermia mechanism (Davies, 1996, 1998; Hoyle and Wickramasinghe, 1999). In this scenario Earth could have been inoculated by either the same life or different forms of life. In the latter case there is the possibility of multiple points of origin, or multiple geneses at a single place of origin (*e.g.*, Mars).

Is there any *a priori* reason to expect more than one biogenesis event on Earth? Little is known

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about the expected duration needed for life to emerge on an Earth-like planet, or the necessary physical and chemical circumstances. Estimates of the time scale for life to emerge from non-life range from a few million years (Oberbeck and Fogelman, 1989; Lazcano and Miller, 1994) up to billions of years or even longer (Carter, 1983). 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 favor of the hypothesis that life forms easily and often. In a statistical analysis, Lineweaver and Davis (2002) used the observational constraints on the rapidity of biogenesis on Earth to conclude that, on Earth-like planets elsewhere in the universe, 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 frustration (Fig. 1). Here we apply the method of Lineweaver and Davis (2002) to estimate the probability of multiple epochs of terrestrial biogenesis (see the Appendix for mathematical details).

OBSERVATIONAL CONSTRAINTS ON A SECOND GENESIS

The history of the Earth may be conveniently divided into an early period of heavy bombardment, $\Delta t_{\text{frustrated}}$, when biogenesis was frustrated by large frequent impacts, followed by a period of the most recent biogenesis, $\Delta t_{\text{biogenesis}}$, that finally led to the extended period in which life on Earth has been continually present: Δt_{life}. These intervals add up to the known age of the Earth:

$$\Delta t_{\text{frustrated}} + \Delta t_{\text{biogenesis}} + \Delta t_{\text{life}} = t_{\text{Earth}} \quad (1)$$

To bracket the time it took life to get started, Lineweaver and Davis (2002) inserted observational constraints on the other intervals into Eq. 1 and obtained a crude estimate:

$$\Delta t_{\text{biogenesis}} = 100^{+500}_{-100}\text{Myr} \quad (2)$$

The duration of the impact frustration of life, $\Delta t_{\text{frustrated}}$, is often assumed to have lasted until the end of the late heavy bombardment (~3.8 Gyr ago). However, the vulnerability of early life to global impact annihilation depended on a number of factors, such as the difficult-to-estimate robustness of early organisms, and the range of available habitats. If the early crust was cool enough to permit colonization of a subsurface zone deeper than ~1 km, then impact frustration may have lasted for only the first ~100 million years until the Moon-forming impact ~4.45 Gyr ago (Cameron, 1997).

Conditions changed rapidly on the early Earth. During the first 100 million years, planetary accretion involved a bombardment that included the Moon-forming impact. Magma oceans lay just beneath the crust, producing high levels of volcanism, and the surface of the Earth may have been an open system of hydrothermal vents. Impacts along with radiogenic heating point to hot environmental conditions (*e.g.*, Sleep *et al.*, 2001; Lineweaver and Schwartzman, 2004). Much evidence, including hyperthermophilia at the base of the universal tree of life, suggests that the Earth started out too hot for life and then cooled into a regime in which hyperthermophilic and then thermophilic life became established, a process interrupted spasmodically by sudden re-heating events caused by spikes in the bombardment rate.

In this paper, we provide a rough estimate of the probability that there was at least one prior epoch of biogenesis before the formation of known life. If large impacts frustrated biogenesis, then as the frequency of impacts abated, there would have been brief quiescent periods when life may have emerged only to be annihilated by the next big impact. The likelihood that this was the case depends on the durations of the quiescent periods (1–100 Myr) and of the most recent epoch of biogenesis ($\Delta t_{\text{biogenesis}}$). For simplicity, we make the default assumption that the inferred time scale of the single instance of biogenesis that led to known life is characteristic of the other possible epochs of biogenesis (Fig. 1).

EVIDENCE FOR ALIEN LIFE ON EARTH

Henceforth we shall refer to other samples of life arising *de novo* as "alien life." If life began on Earth more than once, either having emerged here or establishing itself by colonization from elsewhere, the question arises as to whether any record of alien life remains. 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, by other environmental insults, or by ancient ancestors of known life. (ii)

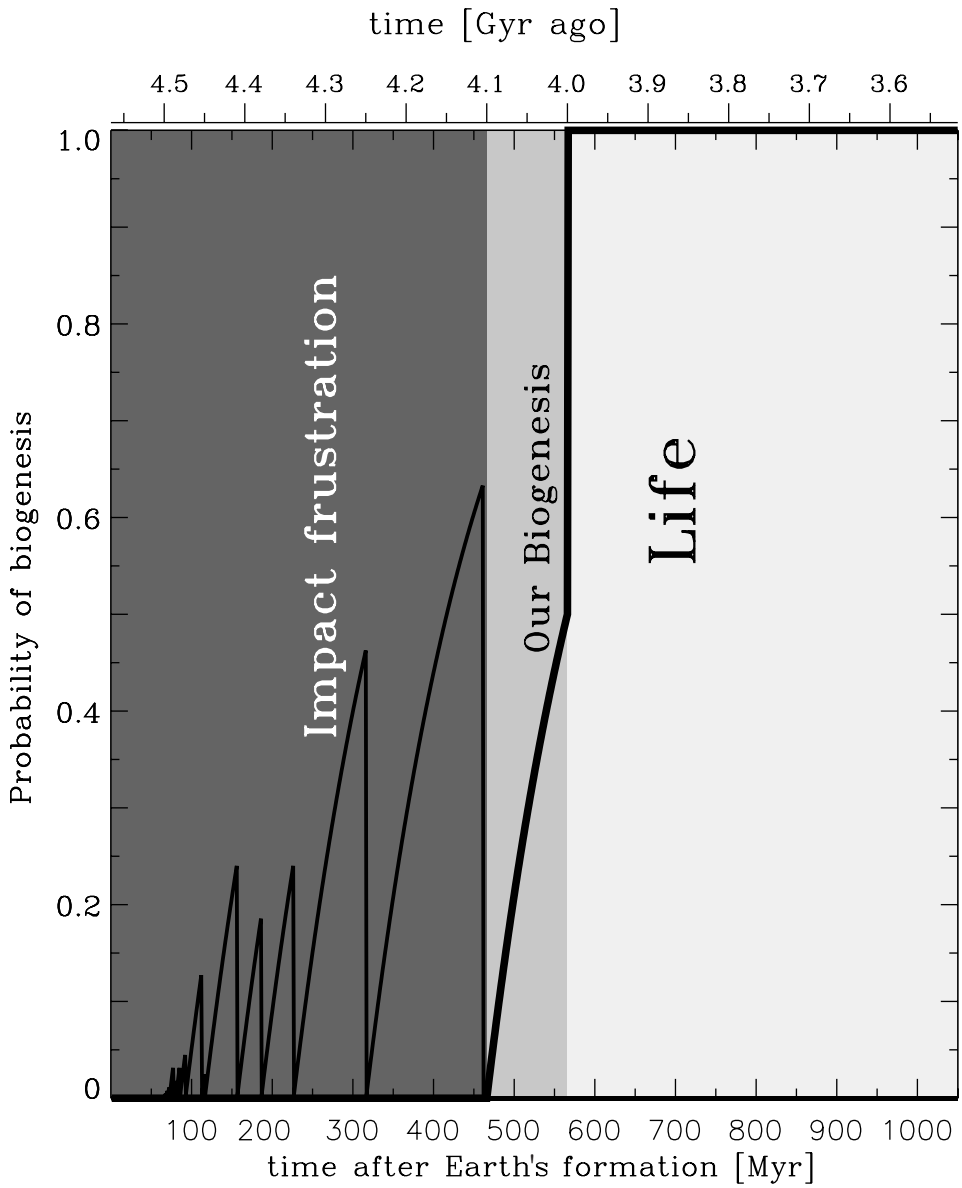

FIG. 1. The probability of biogenesis during multiple and increasingly longer quiescent periods of the first billion years of Earth's history. As an example, we show known life having formed between 4.1 and 4.0 Gyr ago and then resisting extinction from subsequent impacts that included the late heavy bombardment (3.8–3.9 Gyr) associated with the largest lunar mare. It was assumed that periodic large impactors (diameter $D > 500$ km) sterilized the Earth and eliminated any life that may have emerged (Sleep *et al.,* 1989) prior to biogenesis (assumed to have been a process of molecular evolution). The time period of biogenesis, $\Delta t_{\text{biogenesis}}$, was estimated to be 100 Myr [see Lineweaver and Davis (2002) for a review of estimates of this time scale]. The probability of biogenesis during $\Delta t_{\text{biogenesis}}$ was estimated at 50% ($q = 0.5$ in Fig. 3 of Lineweaver and Davis, 2002). In this example the probability of at least one epoch of a second biogenesis is ~0.9 (see Appendix for mathematical details).

At least one sample of early alien life survived and co-existed for an extended period with known life, which perhaps affected the latter's 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 or arriving today.

If hypothesis (i) were the case, direct evidence for multiple geneses would be 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 (>3.8 Gyr ago) that may have preserved traces of alien terrestrial and/or known life could be recovered from the Moon or Mars. The fact that alien life may not have survived the late heavy bombardment does not logically preclude the existence of biological consequences it may have left behind, but identifying its biomarkers, especially those from early Archean rocks, presents a formidable challenge.

Hypotheses (ii) and (iii) imply that alien life was able to survive the bombardment. One possibility is survival in subsurface refugia. If alien microbes dwelt more than ~1 km below ground, they may have survived even the largest impacts if they were located far enough away from the impact sites. This possibility would depend on the rate of cooling of Earth's crust. The second possibility is that material ejected from Earth by impacts could have preserved a fraction of the microorganisms embedded therein. Some of this material would have gone into solar orbit, with a fraction of that returning to Earth after surface conditions returned to normal, thereby "recolonizing" a sterilized planet. A variant of this second possibility is that some ejected material eventually impacted other planets. During the first billion years of Solar System history, Mars [and possibly Venus (Grinspoon, 2004)] was a favorable environment for life. Terrestrial organisms might have colonized Mars (or *vice versa*), and Earth-life might have returned later in Mars ejecta.

Hypothesis (iv) is normally discounted based on 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 (Darwin, 1871). However, microbial life may not have been 100% efficient in consuming available resources. As an example, consider the nonconsumption of the energy-rich hydrocarbons in fossil fuels by microorganisms.

Another shortcoming of the above objection is that it ignores the possibility of "genetic takeover"—that life might originate with one chemical system, and then evolve another. This is the case in the hypothesis of Cairns-Smith (1982) of clay life. If life began sluggishly with clay crystals and was then "taken over" by nucleic acids and proteins, it is conceivable that new forms of clay life have continued to emerge. It might even be possible to observe some form of this type of biogenesis if the incubating environment was sufficiently undisturbed by the activities of known life. Finally, the objection assumes that only one general form of life is possible. If different forms of life can emerge in different physical and chemical environments, then the exhaustion of one life form's resources would not preclude the emergence of another life form at a later date.

A second objection to hypothesis (iv) is the instability of a situation in which life forms co-exist yet compete for resources. If Earth were contiguously inhabited by Type A life and Type B life, then whichever form enjoyed a differential advantage could come to predominate and eventually drive the other form to extinction. This argument, however, does not apply to known life. For example, Bacteria and Archaea are distinct forms of life that occupy similar ecological niches, yet they have co-existed for at least 2 billion years.

A more serious objection is that biogenesis involving organic synthesis (as opposed to inorganic synthesis in clay crystals) almost certainly required reducing conditions. The build-up of free oxygen through oxygenic photosynthesis, even at relatively low levels, would have acted to frustrate further organic synthesis. However, the accumulation of atmospheric oxygen was a slow process, and to reach levels that would interfere with organic synthesis would be unlikely to have occurred before about 3 Gyr (Catling and Zahnle, 2002; Ono *et al.*, 2003).

For all these reasons it is entirely conceivable that more than one form of life may have arisen and even co-existed on Earth. Assuming that evolutionary convergence was not so strong that different genesis events did not rapidly evolve identical biochemical systems and genetic codes, the question then arises as to how we might identify a second sample of life in a terrestrial setting.

The superficial retort that alien organisms around us have not yet been identified may be countered in several ways. Alien life would in all probability be restricted to microbes. Scientists have devised a suite of tools customized for studying known life; alien microbes are likely to be missed or discarded in even the most general microbiological analyses involving bio-prospecting (Leadbetter, 2003). 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 properties that do not reveal them as living organisms. Finally, they may be dormant and inactive, awaiting physical conditions different from those associated with known

life. For all these reasons we could be surrounded by living, dormant, or dead alien microbes without being aware of it. That (i) most bacteria are non-cultivable, (ii) a new domain of life was discovered only 15 years ago (Woese, 1990), (iii) an entire phylum of Archaea known as Koryarchaeota is known only from its environmental DNA, and (iv) the first member of a new phylum of Archaea—Nanoarchaeota—was found recently (Huber *et al.,* 2002), all strongly suggest that the microbial world has many hidden surprises, one of which may be alien life (Fig. 2).

To identify alien life in a terrestrial environment requires a more careful analysis than scientists have applied hitherto (Paster *et al.,* 1998). Evidence might be found in a number of ways.

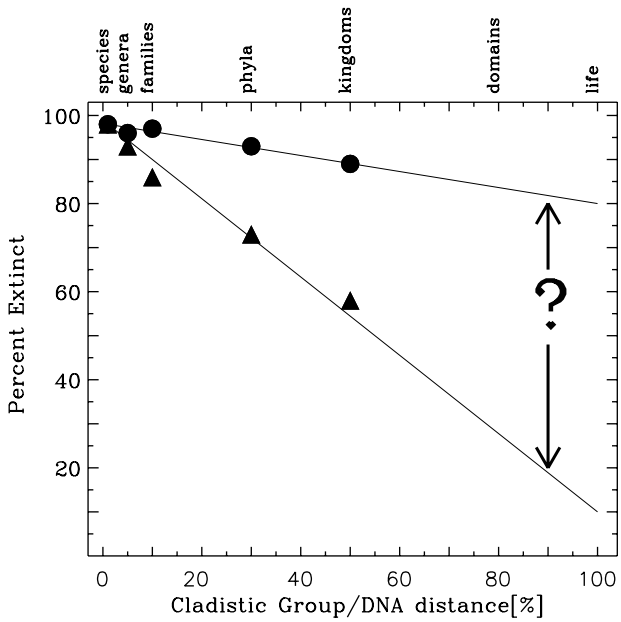

FIG. 2. At any cladistic level, we can estimate the ratio of the number of clades that have gone extinct to the number of clades that have ever existed. We call this the "percent extinct." For example, it is estimated that there are between 10 and 100 million species of animals, plants, or fungi alive on Earth today. If the number of species of animals, plants, or fungi that have ever lived is at least 10 times larger, then the percent extinct for species would be at least 90%. As illustrated here, similar rough estimates of percent extinct could be calculated for higher-level clades using paleontological analyses similar to the work of Raup and Sepkowski (1986) on genera and families (1986) and Alroy *et al.* (2001). For example, different species of the same genus have on the order of 0–1% difference in 16S rRNA, while different genera of the same family are more different from each other and have on the order of 1–5% difference in 16S rRNA. The three domains of life (Archaea, Bacteria, and Eukarya) may be different from each other at about the 50–90% level (Pace, 1997). Even the crudest estimates of these quantities allow us to distinguish between the two lines shown here. If the data are more like the triangles, then we probably know all the domains and forms of life that have ever existed. However, if the data are like the circles, then our ignorance of even higher cladistic levels is large, and there probably are or have been many domains and forms of life that we know nothing about.

Geological evidence

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, nonracemic 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 is given by Brocks *et al.* (1999).

Direct evidence for early alien life might have been preserved in Archean rocks ejected from Earth by impacts and are now located, relatively undisturbed, on the surface of the Moon or Mars. Identifying these rocks and any evidence of alien life they might contain, however, would be extremely difficult.

Novel environments

Alien life might occupy environments that are lethal to known life. Further efforts to search extreme natural and 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. Just what this upper limit might be is the subject of some debate, but somewhere approaching 130°C seems reasonable based on the current upper limit of 121°C (Kashefi and Lovley, 2003).

Other possibilities are the high atmosphere (Wallis *et al.,* 2004), the very deep subsurface (>5 km) (D'Hondt *et al.,* 2004), grossly contaminated aquifers and lakes, and very low-temperature locations. 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 conceivable 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 replicated (Woese, 1998). Studies of ancient gene duplications may one day identify such genetic anomalies (Gribaldo and Cammarano, 1998).

Biological filters

If alien life flourishes in similar environments as known life, then looking in novel environments is unnecessary. Rather, we need to devise a means by which to separate known from alien microbes. Any physical characteristic, *e.g.,* size, membrane structure, might differentiate between them. An example, albeit controversial, is the so-called nanobacteria or nanobes discovered in nature, which seemingly are too small to contain ribosomes and, therefore, are potentially alien (Folk, 1993; Uwins *et al.,* 1998). The problem of simply plucking an alien microbe from a general biological setting, however, is daunting. Very few known microbes, let alone alien microbes, can be cultured. An alien microbe might look superficially like a known bacterium; only a genetic analysis would disclose its exotic nature. Clearly a more systematic approach is necessary.

The primer sets that are currently being used in bio-prospecting could be generalized (Paster *et al.,* 1998). An example of the necessity of this is the discovery via microscope of a novel Archeon that grows attached to *Ignococcus* but has such a divergent 16S rRNA sequence that no universal primer could detect it (Huber *et al.,* 2002). 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 and separated using flow cytometry (Michael Gillings, private communication).

Another possibility concerns chirality. The origin of biological chirality remains contentious (Eliel *et al.,* 1994), 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 assist the co-existence of alien and known life forms. It would also provide a means to detect alien life. If a nutrient broth with opposite chirality contents ("anti-soup") were used as a culture medium, known life might be unable to grow, but oppositely chiral alien life may still flourish (Pauline Davies, private communication). Experiments with anti-soup have been performed on the sterile soils of the Atacama desert (Navarro-González *et al.,* 2003), but as far as we are aware they have not been used to study more promising locales for alien life.

Amino acids with opposite chirality occur naturally in the environment. Their origin is usually attributed to the racemization of decaying organisms (Bada, 1999; Bada *et al.,* 1999). 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 biomarkers for past anti-chiral life, especially if such life used a different set of amino acids from known life. On the other hand, this material would seem to offer a potential food source for any anti-chiral life.

Finally, if a means could be found to interrupt genetic machinery employing the universal genetic code, then any remaining signs of metabolism are likely to be indicative of either alien or 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 labeled release experiments similar to the Viking procedures, or directly from microscopic searches and gene sequencing.

WHAT IS MEANT BY A "SECOND SAMPLE" OR "ALIEN LIFE"?

Our analysis conceals some difficult conceptual issues with regard to how to define a second sample of 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 rather than multiple branches sprouting from a common trunk.
2. As in scenario 1, but the same form of life emerges, either independently 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 example (Strauss *et al.*, 1996).
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 code (Freeland and Hurst, 1998). The same selective pressures might conceivably have generated the same code more than once.

Conversely, just how different must two samples of life be for us to be sure they descended from distinct origination events? Organisms with 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 that produced 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.

Another important distinction would be a form of life that did not use ribosomes to manufacture proteins, or perhaps didn't use proteins and/or nucleic acids at all, but employed some radically alternative chemistry. Some imaginative proposals have been made (Feinberg and Shapiro, 1980). 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 we have tacitly adopted a 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 sense to discuss multiple origins, just as one may envisage bush fires starting independently at different locations. We make this assumption implicitly in Fig. 1. The second possibility is that there is no clear 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 for known and alien life. But even in this case, one would be justified in talking about multiple origins if the genesis events took place in, say, different windows of time between global sterilizing impacts, or on different planets. Our present analysis does not generally discriminate between these various alternatives of multiple origins, but a more refined treatment could seek to 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.

SUMMARY

Whether life is easy or hard to get started remains uncertain despite decades of research. It is often tacitly assumed that life is widespread in the Universe, implying that, in the absence of an efficient panspermia process, life forms readily. This belief is bolstered by the fact that life established itself on Earth soon after conditions became congenial. But if life is likely to emerge from

non-life with high probability on other planets, it is also likely to have emerged on Earth more than once. Our analysis confirms this expectation by deriving moderate to high probabilities for multiple geneses using plausible assumptions about the rapidity of life's emergence on the early Earth. Thus we propose the default assumption should be that Earth hosted more than one form of biology, rather than the more orthodox position that life as we know it has always been alone.

Multiple geneses can result in sequential independent biologies or in multiple contemporaneous biologies. In the latter scenario, we propose that the default assumption should be that one or more alternative biologies should be expected, unless a plausible reason can be found why the emergence of one form of life drastically inhibits the subsequent formation of another. We are not aware of any strong argument to this effect. This raises the question as to whether other forms of life co-exist with known life today. We discussed ways to obtain evidence for such aliens. Our conclusion is that alien microbes could exist on Earth today and have remained undetected by our best efforts.

MATHEMATICAL APPENDIX

The probability f, as a function of time for biogenesis to occur on Earth during any interval of time, is given by Eq. 7 of Lineweaver and Davis (2002):

$$f_i(t) = 1 - (1 - q)^{t'/\Delta t_{\rm bio}} \quad \text{(A1)}$$

where $t' = t - t_i$ for $t_i < t < t_{i+1}$, and t_i and t_{i+1} are the times of life-sterilizing impacts bracketing the ith quiescent period ($\Delta t_i = t_{i+1} - t_{\rm i}$) during which the molecular evolution that leads to life could proceed. Also, q [constrained to be greater than $\sim$0.1 at the 95% confidence level in Lineweaver and Davis (2002)] is the probability of biogenesis in the duration $\Delta t_{\rm bio}$. This is an estimate of the average time required for biogenesis, and is assumed to be close to our estimates of how long the most recent epoch of biogenesis took, *i.e.*, we assume $\Delta t_{\rm bio} \sim \Delta t_{\rm biogenesis} \sim$100 Myr (Eq. 1). We also choose the probability q of biogenesis during this period to be $\sim$0.5, consistent with the $q > 0.1$ limit found in Lineweaver and Davis (2002). This choice means that $\Delta t_{\rm bio}$ may be thought of as the half-life for non-life to transform into life. Figure 1 illustrates a plausible statistical analysis of the proposal that life arose on Earth and became extinct once, and possibly many times, before it arose and survived as the precursor to current familiar terrestrial life.

The probability of not having any biogenesis during the period labeled "Impact Frustration" in Fig. 1 is

$$P_{\rm nolife} = (1 - f_{1\rm max})(1 - f_{2\rm max})(1 - f_{3\rm max}) \ldots = \Pi_{i=1,N}\,(1 - f_{i\rm max}) \quad \text{(A2)}$$

where $f_{i\rm max}$ is the maximum value reached by $f_i(t)$ (see Eq. A1) during the ith quiescent interval Δt_i between sterilizing impacts. The product on i is over some number N of the longest quiescent intervals.

Estimates of the bombardment rate of the early Earth are based on cratering rates of the moon, scaled for the larger size and mass of the Earth (Zahnle and Sleep, 1997). Hartmann *et al*. (2000) estimated that between 4.55 Gyr ago and 4.1 Gyr ago the impact rate fell from a value 10^9 times higher than it is today to a value 10^3 times higher. That is, within the critical period of impact frustration the impact rate fell by a factor of 10^6. Since the durations of the quiescent periods between the largest impacts are roughly inversely proportional to the impact rate:

$$\Delta t_i \propto 1/(\text{impact rate}) \quad \text{(A3)}$$

the average duration of the quiescent intervals increased by a factor of 10^6 between 4.55 and 4.1 Gyr ago, and thus it is probable that if a second example of biogenesis occurred, it would be towards the end of impact frustration. This is illustrated in Fig. 1; however, for convenience the dynamic range of over a million ($= 10^9/10^3$) is restricted in Fig. 1 to only 1,000. Note that there is considerable uncertainty about the distribution in time of large impacts because later impacts tend to obliterate the record of earlier impacts. Some commentators (Hartmann *et al.*, 2000) have suggested that there was a surge of large impacts toward the end of the bombardment period, at about 3.9–3.8 Gyr. The preliminary treatment reported here does not incorporate this suggestion.

The probability $P_{\rm alien}$ that alien biogenesis occurred at some time within this series of quiescent periods is

$$P_{\rm alien} = 1 - P_{\rm nolife} = 1 - \Pi_{i=1,N}\,(1 - f_{i\rm max}) \quad \text{(A4)}$$

In Fig. 1, we have chosen an example with parameters $q = 0.5$, $\Delta t_{\rm bio} = 100$ Myr, and $N = 14$, with a variety of Δt_i, roughly consistent with Eq. A3. With these values we get $P_{\rm alien} \sim 0.9$ as a plausible estimate that alien life evolved on Earth before the origin of normal life. Using $q = 0.3$ reduces $P_{\rm alien}$ to 0.7, and reducing $\Delta t_{\rm biogenesis}$ to 10 Myr gives $P_{\rm alien} \sim 1$ for both $q = 0.3$ and 0.5. If it takes only a short time (on average) for life to get started [such as the <8 Myr estimate of Lazcano and Miller (1994)], then the probability of a second genesis sometime during impact frustration is relatively higher. That is, if $\Delta t_{\rm bio}$ is "small" (1–10 Myr) compared with the durations of the quiescent intervals between large impacts, the probability of a second biogenesis is relatively larger. If $\Delta t_{\rm bio}$ is "large" (100–1,000 Myr) the probability of multiple epochs of biogenesis may be negligible. The choice of $N = 14$ as the number of sterilizing impacts is roughly consistent with the poorly known number of impactors in the diameter size range $D > 500$ km (Sleep *et al.*, 1989; Hartmann *et al.*, 2000).

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