Acta Astronautica 73 (2012) 250–257

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Footprints of alien technology

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ARTICLE INFO

Article history:
Received 13 January 2011
Received in revised form
6 June 2011
Accepted 21 June 2011
Available online 26 August 2011

Keywords:
SETI
Astrobiology
Drake equation
Origin of life

ABSTRACT

If alien civilizations do, or did, exist, their technology will impact their environment. Some consideration has been given to the detection of large-scale astro-engineering, such as Dyson spheres. However, a very advanced technology might leave more subtle footprints requiring sophisticated scientific methods to uncover. We must not overlook the possibility that alien technology has impacted our immediate astronomical environment, even Earth itself, but probably a very long time ago. This raises the question of what traces, if anything, might remain today. I shall consider the possibilities of biological, geological and physical traces, and suggest ways that we might search for them.

1. The birth of astroforensics

The question of whether or not we are alone in the universe is one of the oldest that human beings have asked. For centuries the issue remained in the provinces of theology and philosophy, but in recent decades it has entered the realm of science. The question would be immediately answered if SETI astronomers succeeded in detecting a signal directed at Earth from an extraterrestrial civilization. While this remains the holy grail of SETI, the scenario seems extremely unlikely at this time, for a simple reason. Even taking optimistic estimates, the nearest civilization is likely to be located at least several hundred light years from Earth. The denizens of this hypothetical civilization will therefore see Earth as it was several centuries ago, before the modern technological era. They may deduce from the detection of agriculture and rudimentary engineering that, any millennium soon, Earth's inhabitants may develop radio telescopes, but it would make no sense for them to start deliberately beaming messages at us until they are sure we are on the air. That could not happen even in principle for a few centuries yet, until our first feeble terrestrial radio transmissions, leaking into space at the speed of light, finally reach them.

However, it is not necessary for us to pick up an actual message, crafted for mankind and deliberately beamed at our planet, in order to be able to deduce that we are not in fact alone in the universe. It would be sufficient for us to detect incontrovertible signs of alien technology in any form whatsoever. So alongside the pursuit of traditional radio SETI, which I strongly support, we should expand the search to cover footprints of alien technology in the most general sense, including indirect evidence. I thus advocate that, rather than leaving SETI to a small and heroic band of radio astronomers, we should mobilize the entire scientific community to "keep their eyes open" for telltale signs of alien technological activity. In this paper I outline some of the things that scientists might watch out for. I name this aspect of SETI "astroforensics". Like forensic science, investigators must attempt to distinguish between "natural causes" and the hand of agency (as in natural death versus murder). In astroforensics, as in conventional forensic science, the hallmarks of intelligent agency (i.e. artificiality) might in practice be very subtle, and require sophisticated scientific analyses to tease out.

2. Existing suggestions

During the 50 years of conventional radio SETI, suggestions have been made from time to time of how alien technology might leave a detectable signature, other than

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doi:10.1016/j.actaastro.2011.06.022

via a deliberately beamed radio or optical message. These suggestions include the following:

- Extraterrestrial domestic radio traffic, or beamed radio messages intended for someone else that just happens to pass our way. Unfortunately these signals would almost certainly be orders of magnitude too weak to be detected using current technology, or would be indistinguishable from noise.
- Beacons: an advanced civilization, perhaps towards the center of the galaxy, may have made a powerful radio or optical beacon that sweeps the plane of the Milky Way like a lighthouse and could endure long after the civilization has vanished. From Earth the beacon would appear as a brief radio or optical pulse, repeating perhaps after many months or years. Radio astronomers have detected many such pulses. With the possible exception of the so-called ''Wow!'' signal (see, for example, [1]), few of the transient events so far detected are sufficiently odd as to constitute candidates for artificiality. However, SETI currently lacks the dedicated technology to check, for example, by observing the sources for extended durations for signs of a repeat. A different suggestion along the same lines was made by Frank Drake; perhaps a distant civilization would dump a rare element such as technetium in its host star so that its spectrum would stand out as ''peculiar''.
- Dyson spheres: a super-civilization might engage in large-scale astro-engineering projects, such as creating a shell of material around their host star (known as a Dyson sphere after Freeman Dyson) to trap a large fraction of the star's heat output, in order to run their industry. Dyson spheres would be distinctive infra-red sources. Limited searches have been made (see, for example, http://home.fnal.gov/~carrigan/infrared_astronomy/Fermilab_search.htm).
- Dormant probes: perhaps the aliens dispatched a probe to the solar system long ago, and it is even now lying dormant, maybe in the asteroid belt or at one of the Earth–Sun Lagrange points, waiting to make contact. Allen Tough's ''Invitation to ETI'' to log onto a dedicated website is one example of a search for such a probe (http://ieti.org/). Another possibility would be to try and ''wake up'' any such probe by beaming powerful ''hello'' radio messages to the Lagrange points. As far as I know this has not been tried. We could also try optical searches for a probe. Although limited optical searches of the Earth–sun and Earth–moon Lagrange points have been made (e.g. [2]), there has as yet been no systematic effort.

3. Alien visitation

It has long been conjectured that some fraction of alien civilizations might expand beyond their home planets and spread across the galaxy, for reasons of exploration, colonization or something else. This raises the possibility that the solar system, and even Earth itself, may have been visited at some stage in its history. We could look for traces of such a visit/sojourn. This topic was famously addressed by Enrico Fermi in his ''where is everybody?'' comment made in 1950, often referred to as the Fermi paradox (see, for example, [3]). It rests on the observation that the solar system is 4.5 billion years old but the galaxy is much older. There were stars and planets around long before Earth even existed, and even at slow propulsion speeds alien spacecraft could cross the galaxy in a tiny fraction of the age of the galaxy.

There is no obvious reason why our own astronomical epoch favours the emergence of civilizations, so in the absence of any reason to the contrary we can assume that the rate at which civilizations emerge is roughly uniform over Earth's history. Thus the probability per unit time of a ''visit'' will be also be roughly uniform over a multi-billion-year time frame or, more likely, on a gradually rising trend. In any case, the expected arrival date for an alien visit/sojourn is likely to be $>10^8$ years ago. The key point is that this event is extremely unlikely to have taken place within the period of human habitation of Earth, and is likely to have happened hundreds of millions or even billions of years ago. The question then arises of what traces, if any, might survive from an extraterrestrial visitation event/sojourn after, say,100 million years? The answer is ''not much,'' but four possibilities spring to mind.

1. Nuclear waste: Nuclear substances, such as spent fuel or contaminated material, can have an immense half life, and if dumped or buried on Earth or another body in the solar system would certainly leave a distinctive trace at this time, as the case of the Oklo natural reactor in Gabon demonstrates. (This uranium deposit went critical about 2 billion years ago, and retains distinctive radio-nuclides—see, for example, [1].) If a deposit of plutonium– an excellent nuclear fuel – were found, even in trace quantities, it could only have an artificial origin, because the half life of plutonium is much less than the age of the solar system. All natural sources of this element have long since decayed to negligible proportions.
2. Large-scale mineral processing or geo-engineering: Mining or quarrying could leave scars that would persist for geological times, although the evidence may well by now be buried beneath overlaying strata (just as the 65 million year old Chixculub impact crater, associated with the death of the dinosaurs, is no longer visible). But buried quarries or mineral dumps could still be revealed from geological surveys. Quarrying or construction on the moon or asteroids would persist conspicuously for much longer, and scrutiny of the Lunar Reconnaisance Orbiter data would be a useful exercise. Exotic technologies, such as those exploiting magnetic monopoles or dark matter energy sources, might leave distinctive microscopic traces in the geological record, such as tracks in mica [4].
3. Biotechnology: Genetic information can have extraordinary longevity, on account of replication, repair and selection mechanisms. Our genes contain some biological information that has been little changed for billions of years. An alien expedition, probe or colony might have engaged in biotechnology for a variety of reasons: to assist in mineral processing, food

production, pharmaceuticals, "terraforming"-type geo-engineering or basic research (see also point 4). Evidence for alien tampering with terrestrial genomes might well persist to this day, buried in genetic data. An alternative – in fact, more plausible – scenario is that the aliens would have created *de novo* an artificial "shadow biosphere" of alternative life in the form of micro-organisms more suited to their own biochemistry as opposed to ours. Remnants of this shadow biosphere, or Life 2.0, might well be all around us, unrecognized for what it is [5–7]. A major research program is currently underway to search for a shadow biosphere, albeit one of natural rather than artificial origin. This scenario is a variant of Crick's directed panspermia hypothesis [8], which postulates that the original life on Earth was deliberately seeded by aliens.

4. Artifacts and "messages in a bottle": Conventional construction work on Earth's surface would be most unlikely to survive 100 million years of tectonic activity, glaciations, weathering, cosmic impacts, etc. If an alien expedition wished to leave a clear message for posterity right here on Earth, a good way of doing that would be to upload the message into the genomes of terrestrial organisms, either belonging to the known, or to a shadow, biosphere. It would be simple even for an un-crewed alien lander probe to insert the necessary genetic material, preferably in a way that does not compromise the functionality of the host organism but is nevertheless deeply conserved over time through many generations. A systematic search of genomic sequence data, starting with micro-organisms with the most ancient lineages, for anything that stands out (e.g. a series of prime numbers in the 4 nucleotide bases) would be extremely simple and inexpensive to carry out. One can even conceive of an alien message being uploaded remotely using viruses (which insert DNA naturally) dispatched in vast numbers across the galaxy from the aliens' home planet. Using living cells may not be the only way of leaving or inserting a "message in a bottle" with a billion-year potential longevity [1].
5. Software searches. SETI is acknowledged to be a needle-in-a-haystack search, without any guarantee that there is even a needle to be found. The subject is therefore dominated by the efficiency with which vast databases can be trawled for signatures of artificiality. SETI@home is an obvious emblem of this conundrum: how to spot the signal amid the noise? Much hope is invested in Moore's Law for progressively making database searches quicker and cheaper. Targeted searches, for example applying standard pattern recognition algorithms to the output of SETI antennas, are already demanding enough, but a broader approach to SETI is orders of magnitude harder.

Traditional radio SETI is predicated on the assumption that an alien civilization would broadcast beamed narrow band signals at target planets, but this is obviously a very anthropocentric scenario. What can we know about the technology, let alone the agenda, of a truly alien super-civilization that may have evolved over tens of millions of years, and may well have progressed to a post-biological phase of artificial and networked information-processing sentience and agency? About all that can be said is that all bets are off. The footprint of a ten million year old technology might manifest itself in a completely unexpected fashion. It could be incredibly subtle and inconspicuous, or "hiding in plain sight."

What strategy can humans adopt to search for such a footprint? First, we must abandon any preconceptions about where traces of alien intelligence/technology may be found or what form they might take. The search should be for the very broadest signatures of artificiality. There is no need to confine ourselves to radio astronomy, though the decades of honing radio SETI will continue to give it pride of place in a broader SETI program. All the sciences are currently generating vast databases, any of which might conceal evidence for alien technology or manipulation. Second, the question of cost effectiveness dominates all. If a search is easy and cheap to carry out, it is worth doing anyway, irrespective of how plausible the chances of success may be. An excellent example is provided by "genomic SETI." The idea that ET may have uploaded a message into the DNA of terrestrial organisms is obviously a wild and fanciful one, but it is one that is very easily investigated. Genomes are routinely being sequenced anyway, and the data is available on the internet. All it takes is to run the existing data through an algorithm that looks for unusual patterns, which could be accomplished at almost no cost. So why not try it? Much harder to determine would be evidence for ancient genomic tinkering, which might result from long ago alien biotechnology.

4. Testing the cosmic imperative

When SETI began 50 years ago, it was regarded as a rather eccentric enterprise on the fringes of science. The prevailing view in the 1960s was that life on Earth is a bizarre fluke, a chemical accident of such low probability that it would be unlikely to occur again in the entire observable universe. Jacques Monod summarized the mood by declaring that "the universe is not pregnant with life," and therefore that "Man at last knows that he is alone in the universe" [9]. George Simpson, one of the great neo-Darwinists of the postwar years, dismissed SETI, the search for intelligent life, as "a gamble at the most adverse odds with history" [10]. Biologists based their pessimistic conclusions on the fact that the machinery of life is so complex in so many specific ways that it is inconceivable it would emerge more than once as a result of chance chemical reactions. Chance assembly of building blocks is exponentially unfavoured, and the odds of assembling any given molecular structure by chance alone very easily falls to infinitesimal levels. Francis Crick captured this common opinion eloquently when he wrote "The origin of life appears… to be almost a miracle, so many are the conditions, which would have had to be satisfied to get it going" [11]. In short, to profess belief in extraterrestrial life of any sort, let alone intelligent life, in the 1960s and 1970s, was tantamount to scientific suicide. One might as well have expressed a belief in fairies.

What, then, has changed? Why is it now scientifically respectable to search for life beyond Earth? Oft cited as an explanation is the fact that many extra-solar planets have now been discovered, with a strong likelihood that billions of earthlike planets may exist in our galaxy alone. As a result, there are probably a very large number of available habitats for life of the form that we know. However, this explanation is weak. Although no planets were identified beyond the solar system until recently, most astronomers nevertheless supposed all along that they existed. Sometimes astrobiologists cite the recent discovery of many species of organic molecules in space, providing evidence that abundant "raw materials" for life are scattered throughout the universe. That may be true, but the path from simple building blocks such as amino acids to a metabolizing, replicating cell is so long and tortuous, the fact that the first small step might have already been taken in space is almost completely irrelevant. Then there is the "follow the water" fallacy. Wherever there is liquid water on Earth, there seems to be life, therefore, it is sometimes claimed, when we find water on other planets and moons, life should exist there too! Water does in fact seem to be abundant in the solar system and beyond, so (it is reasoned) life should also be abundant. Unfortunately this simplistic reasoning confuses a necessary with a sufficient condition. To be sure, liquid water is *necessary* for life (at least as we know it), but it is far from *sufficient*. The reason life on Earth inhabits almost all aqueous niches is because Earth has a contiguous biosphere, and life has *invaded* those niches; it has not arisen there *de novo*. Another reason given for the current optimism about life beyond Earth is the dawning recognition that life can survive in a much wider range of physical conditions than was recognized hitherto, opening up the prospect for life on Mars, for example, and generally extending the definition of what constitutes an "earthlike" planet. But this at most amounts to a factor of two or three in favor of the odds for life. Set against that is the *exponentially* small probability that any given complex molecule will form by random assembly from a soup of building blocks. In short, *habitability does not mean inhabited*. It is natural that we should concentrate on the habitable planets in our search for life – by the "keys under the lamppost" principle –but at this stage we cannot put any level of confidence – none at all – on whether such a search will prove successful.

The correct explanation for the shift in mood lies, I suspect, with fashion. The pendulum has swung from skepticism to credulity without very much changing on the actual scientific front. True, we do know far more today about life's basic processes, and about the physical conditions on other planets. But we still know almost nothing about the overwhelmingly important factor, namely, the probability that life will emerge on a planet given that it resembles Earth, for the simple reason that we have little or no idea beyond a few general scenarios and just-so stories how life actually emerged from non-life.

My point is thrown into sharp relief by studying the famous Drake equation, first written down by Frank Drake in 1961 at the dawn of SETI to guesstimate the number of communicating civilizations in our galaxy. Here it is:

$$N = R^* f_p n_e f_l f_i f_c L$$

where R^* *is the* rate of formation of sun-like stars in the galaxy, f_p the fraction of those stars with planets, n_e *the* average number of earthlike planets in each planetary system, f_l the fraction of those planets on which life emerges, f_i the fraction of planets with life on which intelligence evolves, f_c the fraction of those planets on which technological civilization and the ability to communicate emerges and L the average lifetime of a communicating civilization.

Today we have good estimates of R^* and f_p, and should soon have a handle on n_e too, when the results of the Kepler mission are released. The last three factors are notoriously hard to predict, but at least we have an accepted and well worked out theory – Darwin's theory of evolution – that could in principle tell us something about the probability of the evolution of intelligence and even of civilization. Once civilizations exist, it is not hard to imagine that at least some fraction will survive for a long time. That leaves the factor, f_l, the number of earthlike planets on which life arises. The uncertainty in f_l completely dominates the right hand side of Drake's equation, and makes discussion of the error bars on the other terms utterly moot. To take a simple (but absurd) illustration, if a single common protein like cytochrome c had formed by chance assembly from an ocean of molecular building blocks, the odds against it happening twice are so large that they dwarf the number of atoms in the universe. But of course, that may not be how life on Earth formed at all. Chance may have played only a subordinate role. The origin of life may have been more "law-like" than "chance-like". There may exist a sort of "life principle" that fast-tracks matter to life given half a chance so that it will emerge more or less automatically wherever conditions permit. Perhaps life is indeed a cosmic imperative, somehow "built into" the laws of physics in a fundamental way, and therefore an expected product of an intrinsically bio-friendly universe. Perhaps. The trouble is these sentiments are philosophical, not scientific. Unlike Darwin's theory of evolution, we have no accepted theory of life's origin, only a collection of scenarios and conjectures. Without a proper theory, it is meaningless to assign probabilities to outcomes. Furthermore, there is nothing in the laws of physics that singles out "life" as a favored state or destination. The laws of physics (and chemistry) are "life blind"—they are universal laws that do not care for biological states of matter specifically, as opposed to non-biological states. If there is a "life principle" in nature, then it has yet to be elucidated. Perhaps such a principle lurks in the realm of complexity theory or information theory or in the properties of self-organizing systems, but so far there is no hard evidence for it. How, then, can we test the audacious and appealing idea of the cosmic imperative?

5. Finding a second sample of life

If we discovered a second sample of life that we could be sure had arisen from scratch, independently of life as we know it, then the case for the cosmic imperative would be immediately made. The most obvious and direct way in which such a discovery might occur is if SETI succeeded. If astronomers were to detect unmistakable signs of alien technology, then although such technology itself might be the product of machine as opposed to biological intelligence, it would almost certainly imply a biological precursor. A message from ET would enable us to assign a value very close to 1 for f_l, on the reasonable assumption that extraterrestrial life is a precursor for extraterrestrial intelligence, and that cosmic-wide panspermia can safely be discounted. Pending that dramatic event, what else might we look for? Future space-based systems such as the proposed Terrestrial Planet Finder might be able to detect the presence of gases in the atmospheres of other planets that would indirectly imply life—such as oxygen and methane in combination. Unfortunately it may be a long time before systems with the requisite resolution are available. Finding life on Mars from a sample return mission or an expedition might resolve the issue, but then again it might not. Mars and Earth are known to trade rocks, and it is clear that at least some fraction of microbial inhabitants of these rocks could survive the journey [12]. By hitching a ride on impact ejecta, Mars life would readily infect Earth, and vice versa, so the two planets are not quarantined and in effect constitute a single weakly coupled biosphere [13].

Sometimes it is suggested that if we make life in the laboratory, it would prove that life starts up easily. But this is another fallacy. Synthetic biology demands sophisticated equipment and technicians, purified and refined substances, high-fidelity control over physical conditions and, above all, an organic chemist who has a preconceived notion of the entity to be manufactured – in other words, an intelligent designer. Astrobiologists want to know, however, how life began without any fancy equipment, purification procedures, environment stabilizing systems and, in particular, without an intelligent designer. Life may be easy to make in the lab, but still be exceedingly unlikely to happen spontaneously. After all, organic chemists can make plastics quite easily, but we do not find them in nature.

Another argument often used in favor of the cosmic imperative is that life established itself on Earth rather rapidly once conditions became suitable. For about 700 million years our planet was pounded by large comets and asteroids. This heavy bombardment phase abated about 3.8 billion years ago, and already by 3.5 billion years ago microbial organisms were flourishing [13]. As Carl Sagan once expressed it, "the origin of life must be a highly probable affair; as soon as conditions permit, up it pops!" [14]. The reasoning, of course, is that because the formation of life on Earth was relatively quick and easy, then life could be expected to arise similarly on other earthlike planets. Unfortunately this argument is also flawed. The reason that Earth was singled out for Sagan's comment is precisely because Carl Sagan specifically, and human beings in general, are the product of terrestrial biology. Now life takes billions of years to evolve as far as beings like us who can study astrobiology. However, Earth's "habitability window" is not unlimited. In about another 800 million years, the sun will be so hot it will boil the oceans, and our planet will become uninhabitable [15]. So there is a finite period of time, roughly four and a half billion years, in which intelligent life had better emerge on Earth, if it is to emerge at all. But unless life had started promptly after the bombardment, it may never have evolved to the level of intelligence before the habitability window closed. It is therefore no surprise that life "popped up" so quickly—it had to, on account of the fact that we are here! This argument has been placed on a more rigorous and quantitative footing by Carter [16] and Hanson [17]. Obviously one cannot draw strong conclusions from a sample of one; the best one can say is that a quick start to life on Earth is consistent both with the cosmic imperative and with the hypothesis that the *average* time for life to form under earthlike conditions is in fact very much longer than the age of the Earth.

All this ambiguity is very discouraging, but there is a glimmer of hope. We might be able to test the cosmic imperative in a more direct way. No planet is more earthlike than Earth itself, so if life does arise readily in earthlike conditions, then surely it should have formed many times over right here. Well, how do we know it did not?

6. The shadow biosphere

According to the orthodox picture, all life on Earth descended from a common origin, often expressed, following Darwin, by analogy with a tree. There is a strong evidence that all life so far studied in detail is closely inter-related: organisms use a universal genetic code, and they all employ nucleic acids to store information and proteins for structural and enzymatic functions. Proteins are made by ribosomes. It is unlikely that so many specific features would have evolved independently from separate origins; rather, they were surely present in a common ancestral organism (often known as LUCA—the last universal common ancestor) and have been retained as frozen accidents. Even the so-called extremophiles – microbes that thrive in conditions that would be lethal to most life that we know – possess the foregoing biochemical features, and share many genes with less exotic organisms. All known extremophiles have been positioned on the same tree of life as you and me.

Nevertheless, it is now apparent that the vast majority of terrestrial species are microbes, and biologists have only just scratched the surface of the microbial realm. Most micro-organisms have not been cultured or characterized, let alone genetically sequenced. At the present time, we simply do not know what they are. One cannot tell by looking whether a microbe is a bacterium or a novel organism with a radically different internal structure and biochemistry. To fully identify a microbe it is necessary to elucidate its biochemistry and molecular architecture, and to obtain some form of sequence information to position it on the tree of life. It is therefore entirely possible that among the billions of microbes contained in, say, a sample of soil or seawater, some are representatives of life as we do not know it – "weird life," to use the preferred term. Even if all microbes so far sampled are standard life, there may be unsampled niches, perhaps beyond the reach of even the hardiest extremophiles, that are inhabited by weird micro-organisms. If so, such organisms might be what McKay calls Life 2.0 [18] – the living descendants of an origin of life quite separate from the one that gave rise to standard life [7].

One scenario for multiple terrestrial origins goes like this. Earth was heavily bombarded by large comets and asteroids for about 700 million years after the formation of the solar system. The biggest impacts delivered such a large amount of energy that they could have boiled the oceans and sterilized the Earth's surface [19]. However, those same impacts would have ejected prodigious amounts of material into solar orbit. Suppose life got going on Earth during a quiescent period between sterilizing impacts, for example, in a 10 million year window. Following the next big impact, Earth's surface was devoid of life, but micro-organisms may have survived within the ejected material. (There is good evidence that microbes are not killed by the shock of planetary ejection: see Hornek et. al., 2002.) Cocooned inside rocks, these microbes would have been spared direct exposure to harsh space conditions, and in particular they would have been shielded from much of the radiation. In a dormant condition, they could have survived for many millions of years [20]. Some fraction of this ejected material will hit the Earth eventually, thus returning viable microbes to their planet of origin. Meanwhile, however, Life 2.0 had started, so Earth would then be hosting two forms of life from two independent origins. This process may have been iterated many times. In such a manner, our planet may once have accommodated, and may still accommodate, multiple forms of life, and multiple trees of life.

Remarkably little attention has been paid to the possibility of weird (i.e. non-standard) life on Earth, although astrobiologists have thought a lot about weird life on other planets. Searches for weird terrestrial life fall into two categories. First is the case of ecological separation. Life 1.0 and Life 2.0 might inhabit non-overlapping regions of physical and/or parameter space. Consider, for example, hyperthermophiles. The current upper temperature limit for known hyperthermophiles is 122 °C. If a different form of microbial life were detected in a deep ocean volcanic vent system occupying a temperature range of, say 160–180 °C, then it would stand out as a candidate for alternative life because of the discontinuity in the temperature range. A list of extreme environments to search for weird life includes, in addition to ocean volcanic vents, strong UV regions such as the upper atmosphere and high plateaux, regions of extreme cold (Antarctica, mountain tops), aridity (Atacama desert), highly saline or high/low pH aqueous environments, heavily contaminated mining sites and high radiation environments such as uranium mines and nuclear waste deposits.

Much harder to identify would be weird microbes intermingled with standard life, especially if they were present at low relative density. Here, two approaches suggest themselves. One could devise a crude filter that would eliminate or at least inhibit the metabolism of standard life in the hope that it would leave any weird life unaffected. Then the weird life would eventually come to predominate. For example, a culture medium laced with a polymer that targets an enzyme like aminoacyl-tRNA synthetase (which attaches specific amino acids to tRNA in conformity with the standard genetic code), and disables it, would stop all standard life in its tracks. Or a polymer loaded with a metallic nano-particle could be devised to target some specific universal feature of standard life, and then the system irradiated with a laser or microwaves to kill the host cells, but leave any weird cells unscathed.

A second approach would be to make educated guesses about the nature of weird life. Synthetic biologists seek to create novel forms of life in the laboratory, so they are adept at imagining alternative ways that organisms could function [21]. The problem about looking for life as we do not know it, is that we do not know quite what to look for. Any general signatures of life, such as carbon cycling or chiral specificity, will be masked by standard life. But if we guess that weird life might exploit a specific molecule, such as an amino acid absent in standard life, then methods could be devised to detect that molecule. An extreme case would be if weird life uses not merely a different suite of amino acids or nucleotides, but a different set of elements. Most biologists think that carbon is essential, but the secondary vital elements are negotiable. One case of interest is phosphorus. According to Wolfe-Simon, arsenic can substitute for phosphorus for many biological functions, and has the added advantage that it offers a redox potential by the reduction of arsenate to arsenite [22]. Poly-arsenates are far less stable against hydrolysis than their phosphorus counterparts, but in a low-temperature environment that may not be too great a disadvantage. A search for arsenic life has begun, by culturing organisms from arsenic-rich environments such as Mono Lake, in P-depleted conditions. Successive As enhancements and P depletions will eventually eliminate all standard life, so that any organisms, which survive, will have radically new biochemistry. Preliminary results look to be deeply suggestive [23].

A final example of a biological filter concerns chirality. Standard life uses left-handed amino acids and right-handed sugars. The laws of physics are, however, indifferent to the chiral signature of organic molecules, and a second genesis might well produce life with the opposite chirality, i.e. right-handed amino acids and/or left-handed sugars. A culture medium made of "mirror molecules" would prove indigestible for standard life, but may be palatable to "mirror" life (i.e. life with reversed chirality). A pilot experiment of this sort was performed by Pikuta and Hoover and yielded intriguing results that led to the identification of a new class of organisms able to (somehow) metabolize L-sugars [24]. These organisms do not appear, however, to be the sort-after "mirror" life, so the situation clearly involves some subtleties. Nevertheless, the use of chirality as a discriminator between standard and weird life remains a promising approach.

It is sometimes argued that had more than one form of life existed on Earth, then a "winner" would emerge to displace the rest. But there is no compelling evidence for this assumption. Bacteria and archaea are two genetically very different forms of microbial life that have peacefully co-existed for three billion years, even though they are competing for resources in similar niches. Survival strategies widespread in one domain (e.g. methanogenesis among archaea) have not spread to the other. Moreover, microbial species represented in small relative numbers are not observed to be ‘‘squeezed out’’ by the majority, but can remain stable long-term components of the biosphere as minority players. If an alternative form of life is ecologically separated from standard life, or has reversed chirality, it would not be in direct competition anyway.

7. Conclusion

After 50 years of SETI, which has been dominated by the search for radio messages, the time has come to take stock and ask how the search can be widened and made more inclusive. In this paper I have argued that searching for signatures of alien technology in the most general sense, as opposed to messages per se, offers many promising and inexpensive new lines of inquiry. The compilation of vast data sets from across the sciences, all of which can be subjected to massive data analysis at low cost, opens the way to many exciting possibilities. I have described some of them in this paper.

The Drake equation remains a convenient way to organize our ignorance of alien intelligence/technology. I argue that the uncertainty in the number N of communicating civilizations is completely dominated by the uncertainty in f_l, the fraction of earthlike planets on which life emerges. Until we know the mechanism by which life arises from non-life, we cannot compute the probability for biogenesis, and so we cannot estimate f_l. That renders any estimates of N completely moot. So SETI is not just a needle-in-a-haystack search, it is a search without any clue as to whether there is a needle there at all, or how large the haystack may be. Therefore, whilst we patiently wait for radio SETI to continue its historic work, the most dramatic advance we could make towards understanding the place of intelligent life in the universe is to narrow the error bars on f_l, which at present stretch all the way from 0 to 1. A dramatic and direct test is to seek evidence for multiple geneses of life on Earth, perhaps in the form of an extant ‘‘shadow biosphere’’. If we find alien life on Earth (alien in the sense of belonging to a separate tree of life with a separate origin) then we cannot argue that f_l is very close to zero, because it would be most unlikely that life would arise more than once on one earthlike planet (Earth) and hardly ever on all the other earthlike planets we now confidently expect to be out there.

To end on a philosophical note, the ramifications of this shift in viewpoint are immense [1]. So long as we know of only a single sample of life, it is possible to argue that biology is a freak local aberration, the product of a chemical fluke so improbable that it will not have happened anywhere else in the observable universe. Although individual human beings may imbue their lives with significance, life as a whole would be a collection of insignificant freak physical systems, restricted to an infinitesimal patch of the cosmos. By contrast, if life is a ‘‘cosmic imperative,’’ emerging more or less automatically in myriad locations, we could say that the universe possesses intrinsically bio-friendly physical laws, so that life could be regarded as having universal significance. If we also obtain evidence of alien technology, then not just life, but mind, could also be regarded as a fundamental, as opposed to incidental, cosmic phenomenon. One could then join with the physicist John Wheeler [25] and declare that we truly are ‘‘at home in the universe’’.

Acknowledgments

It is a pleasure to acknowledge my many friends and colleagues in the SETI community who have over the years helped me shape my thinking on this subject. Frank Drake especially has been a source of inspiration to me throughout my career. Jill Tarter, Seth Shostak and Doug Vakoch of the SETI Institute, Brandon Carter, the astrophysicist, Freeman Dyson, physicist and visionary, Martin Rees the cosmologist, and Steven Dick, the NASA historian, have all greatly influenced my thinking. Carol Oliver has been a close traveling companion through my SETI journey, and Pauline Davies a meticulous critic and confidante of my wilder ideas. Kathryn Denning especially, but all the members of the SETI Post-Detection Taskgroup, have been a valuable source of information and ideas. Last but not least is Allen Tough, whose relentless championing of new and adventurous thinking inspired this paper.

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