

Moving Beyond Definitions in the Search for Extraterrestrial Life

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Abstract

According to the 2015 *Astrobiology Strategy*, a central goal of astrobiology is to provide a definition of life. A similar claim is made in the 2018 *CRC Handbook of Astrobiology*. Yet despite efforts, there remains no consensus on a definition of life. This essay explores an alternative strategy for searching for extraterrestrial life: Search for *potentially* biological anomalies (as opposed to life *per se*) using *tentative* (vs. defining) criteria. The function of tentative criteria is not, like that of defining criteria, to provide an estimate (via a decision procedure) of the likelihood that an extraterrestrial phenomenon is the product of life. Instead, it is to identify phenomena that resist classification as living or nonliving as worthy of further investigation for novel life. For as the history of science reveals, anomalies are a driving force behind scientific discovery and yet (when encountered) are rarely recognized for what they represent because they violate core theoretical beliefs about the phenomena concerned. While the proposed strategy resembles that of current life-detection missions, insofar as it advocates the use of a variety of lines of evidence (biosignatures), it differs from these approaches in ways that increase the likelihood of noticing truly novel forms of life, as opposed to dismissing them as just another poorly understood abiological phenomenon. Moreover, the strategy under consideration would be just as effective at detecting forms of life closely resembling our own as a definition of life. Key Words: Anomaly—Biosignature—Defining criteria—Life—Tentative criteria—Potentially biological anomaly. *Astrobiology* 19, 722–729.

1. Introduction

MANY ASTROBIOLOGISTS seem to believe that a successful search for extraterrestrial life requires a definition of life. As an illustration, a recent *NASA Astrobiology Strategy* (Hays, 2015), coauthored by leading astrobiologists, contains an extensive discussion of definitions of life focused on “[k]ey research questions for defining life” (p 145). Similarly, Part 2 (“Definitions and the nature of life”) of the *CRC Handbook of Astrobiology* (Kolb, 2018) is devoted to a professed need for a definition of life. Yet, despite an impressively large number of candidates, there is currently no consensus on a definition of life; see Popa (2004, pp 197–205) for an extensive list of modern definitions of life, and Tirard *et al.* (2010) for a discussion of the history of recent efforts to define life. All definitions of life thus far proposed face serious problems, ranging from seemingly intractable counterexamples to being either too abstract or too concrete vis-à-vis familiar life to be of much use in searching for truly novel forms of life (Sagan, 1970; Cleland and Chyba, 2002, 2007; Tsokolov, 2009).

The difficulty in reaching a consensus on a definition of life does not reflect a lack of ingenuity on the part of those attempting to define life. For as discussed in Cleland and

Chyba (2002, 2007), Cleland (2012), and Machery (2012), definitions are not the proper tools for answering the scientific question “what is life?” It is beyond the scope of this short essay to develop these arguments; see Cleland (forthcoming in 2019, Chapters 2–3) for a detailed review. Put briefly, definitions are logical devices for explaining the *meanings* of terms in a natural language; they dissect the *concept* associated with a term (by a competent speaker of the language) into a conjunction of necessary and sufficient conditions. Definitions are thus best suited for terms, such as *bachelor*, *garbage*, and *money*, which designate categories carved out by human interests and concerns. The human *concept* of bachelor exhausts the *nature* of bachelors; it is impossible to discover that we are wrong about bachelors being unmarried. In contrast, human concepts do not exhaust the nature of natural categories such as water, quartz, and fire. Unlike the case with bachelor, the human concepts of water and fire can be (and, indeed, once were) badly mistaken. On the assumption that life, like fire, is a natural category, a definition of life is only as good as our current empirical and theoretical understanding of the phenomena of life.

There are reasons for worrying that the current biological concept of life may be mistaken in important ways. If (as most astrobiologists believe) life as we know it on Earth today

descends from a last universal common ancestor, then it represents a single example of life, an example which may be unrepresentative of life in poorly understood and perhaps even unknown ways. Indeed, biochemists have identified modest ways in which life could differ from familiar life in some of its basic building blocks, for example, amino acids, nucleobases, and sugars. As underscored by the many scientifically informed speculations about exotic possibilities for alien life—see, for example, Grinspoon (2003), Bains (2004), Benner *et al.* (2004), Schulze-Makuch and Irwin (2008), and McKay (2016)—astrobiologists don't know how different alien life could be from familiar life, especially in environments different from those found on Earth. Consulting a definition based upon our current Earth-centric concept of life is unlikely to be very helpful in deciding this question, however. Logically speaking, one cannot safely generalize from a single example to all phenomena of the kind concerned unless one has compelling reasons for believing that the example is representative. We don't have such reasons.

The appeal of a definition of life to astrobiologists is nonetheless understandable: Without a definition of life to guide a search for unfamiliar forms of life, how will one recognize it if one encounters it? This problem is exacerbated insofar as most life in the Universe is almost certainly microbial. Complex multicellular organisms are highly specialized latecomers to Earth, appearing in the fossil record only around 635 million years ago. In contrast, there is evidence of microbial life as far back as 4.1 billion years ago (Bell *et al.*, 2015), not long after the origin of our Solar System, approximately 4.6 billion years ago. This suggests that complex multicellular organisms are not inevitable on a planet with life; they emerge only under special, poorly understood, conditions. If there is life on any of the planets and moons of our Solar System, it is most likely microbial. The more a form of microbial life differs from familiar life, in poorly understood or as-yet-unknown ways, however, the more likely that it will be classified, on the basis of a faulty, Earth-centric, definition of life, as just another mysterious nonliving phenomenon.

This essay outlines a strategy—alluded to in Cleland and Chyba (2007) and Cleland (2012)—for searching for extraterrestrial life that circumvents the thorny problem of defining life. In a nutshell: Use *tentative* (vs. defining) criteria to search for *potentially* biological *anomalies* (vs. life *per se*). Unlike defining criteria, the purpose of tentative criteria is not to provide a decision procedure for estimating the probability that an extraterrestrial phenomenon is the product of life. It is to identify extraterrestrial phenomena that resemble familiar life in intriguing ways but also differ from it in unanticipated and perplexing ways for purposes of more in-depth astrobiological investigation. Under a definitional approach, such phenomena are likely to be classified as the product of poorly understood geochemical processes, and indeed this will sometimes be the case. Yet, as discussed below, in the context of illustrations from the history of science, phenomena of this sort provide the best grist for the theoretical mill, challenging our Earth-centric preconceptions about both life and *nonlife*.

2. The Role of Anomalies in Scientific Discovery

Thomas Kuhn (1970) famously argued that the recognition that a puzzling empirical phenomenon is anomalous is a

driving force behind scientific revolutions. An anomaly is a violation of a paradigm-induced expectation about a domain of natural phenomena. Kuhn characterizes (scientific) paradigms broadly as including laws, theories, and other widely accepted scientific beliefs, as well as sanctioned methods and instruments, concerning a domain of phenomena. Paradigms play vital roles in scientific practice, facilitating the construction of hypotheses, design of experiments, and interpretations of results. But they may also hinder the exploration of nature, discouraging certain lines of research and biasing the interpretation of data. According to Kuhn, recognizing that a mystifying result is anomalous, as opposed to merely another puzzle to be solved within the confines of a dominant paradigm, requires a “crisis,” in which the foundations of the paradigm are openly being challenged. In the absence of a crisis, a paradigm literally blinds researchers to the presence of anomalies. They are either not perceived as puzzling or, alternatively, interpreted as puzzles that eventually will be solved using the resources (concepts, laws, methods, etc.) provided by the paradigm.

Kuhn's most widely cited illustration of how paradigms blind researchers to the presence of anomalies is William Herschel's discovery of Uranus (Kuhn, 1970, pp 115–117). Between 1690 and 1780 some of the most eminent astronomers in Europe reported seeing a star in positions that we now know were occupied by the planet Uranus. Twelve years later, Herschel, using a new and more powerful telescope of his own invention, observed that there was something funny about this star: It was disk shaped, the wrong shape for a star, and moved among (as opposed to with) the other stars. Herschel announced that he had discovered a new comet. Intrigued, astronomers all over Europe trained their telescopes—the same second-rate instruments with which they had previously observed a star—on the mysterious object and concluded that Herschel was correct: The object couldn't be a star. Efforts to fit its motion to a cometary orbit were unsuccessful, however. A few months later, Anders Lexell announced that the orbit was planetary. Lexell's announcement was rapidly followed by the discovery of numerous small celestial bodies (asteroids) having planetary orbits. On Kuhn's analysis, astronomers initially failed to recognize Uranus' anomalous (non-star-like) features because they were committed to a “minor” paradigm that provided them with only two perceptual categories (star or comet) for classifying celestial objects beyond Saturn; Saturn was then viewed as the outermost planet.

Because he was trained as a physicist, as well as a historian and philosopher of science, Kuhn focused on the role of anomalies in the physical sciences, citing many additional illustrations of the critical role played by the recognition of anomalies in scientific discovery (Kuhn, 1970, Chapters VI–VIII). Anomalies are equally common in the biological sciences and have played central roles in important biological discoveries. A good illustration is Thomas Cech's discovery of ribozymes, which challenged what Francis Crick (1958) dubbed the “central dogma of molecular biology”; on Crick's version of the central dogma, there is a rigid division of labor between nucleic acids and proteins. Cech and his team weren't looking for ribozymes when they fortuitously stumbled upon RNA molecules that were catalyzing reactions like protein enzymes. They were investigating the newly discovered phenomenon of splicing. Little

was known about how splicing takes place. In keeping with the central dogma, Cech assumed that a (protein) enzyme was responsible. He planned to isolate it by adding enzymes to a purified sample of precursor RNA until they observed splicing activity.

Cech and his team synthesized precursor rRNA from the genes of a ciliated protozoan, *Tetrahymena* (Cech, 1989). To their surprise, splicing occurred in a preparation that they believed lacked enzymes. Extensive efforts to remove the suspected enzyme from precursor rRNA samples failed to halt the mysterious splicing reaction. Cech and his students became so desperate that they considered the possibility that the enzyme might be covalently bonded to the RNA. As Cech confesses in his Nobel Prize lecture, “[t]hat we took this hypothesis seriously provides an indication of how deeply we were steeped in the prevailing wisdom that only proteins were capable of highly efficient and specific biological catalysis” (Cech, 1989, p 659). Perplexed, they suspended the project of isolating the splicing enzyme and focused on other aspects of the splicing reaction. It was more than a year before Cech and his team explored the possibility that they were dealing with a genuine biological anomaly, as opposed to a failed experiment.

The discovery of the Archaea provides another illustration of how widely accepted biological beliefs can delay recognition of the anomalousness of a puzzling discovery. By the middle of the 20th century, the prokaryote-eukaryote distinction was widely heralded as evolutionarily significant. Prokaryotes were classified together in a single kingdom “Monera” (bacteria), and all true (excluding fungi) unicellular eukaryotes were classified as “Protists.” The assumption that this distinction is phylogenetically significant was based on the *prima facie* plausible notion that one can infer genetic relationships from gross morphological characteristics, in the case of unicellular microorganisms the distinctive internal structure of their cells.

The evolutionary significance of the prokaryote-eukaryote distinction began to unravel in the latter half of the 20th century. Using newly developed methods for directly inspecting genomic sequences, Woese and Fox (1977) collected a large database of prokaryote rRNA sequences. To their surprise, some of these “bacteria” (archaea) differed from other bacteria in their genetic machinery more than they differed from eukaryotes. The lipids in the cell membranes of the former were also distinctive, differing from other bacteria as well as eukaryotes. Woese concluded that the alleged evolutionary significance of the prokaryote-eukaryote distinction was mistaken, and proposed accommodating these strange “bacteria” in a new super-kingdom, Archaeobacteria. As Tim Friend (2007) recounts, Woese’s work was not greeted with enthusiasm. Many biologists ignored it, and several eminent members of the biological community made fun of it. Undaunted, Woese continued his investigations and by 1990 was urging an even more radical restructuring of biological systematics, introducing three overarching “domains” of life (Archaea, Bacteria, and Eukarya) and placing four (*viz.*, Protista, Fungi, Plantae, and Animalia) of the original five kingdoms under the domain Eukarya (Woese *et al.*, 1990). It took almost 20 years for Woese’s work to be widely accepted by biologists.

In hindsight, however, it is clear that there were telling signs that prokaryotes don’t form a natural phylogenetic

category. Because microbiologists were working under the prokaryote-eukaryote evolutionary paradigm, however, these signs went unrecognized for what they represent. As a 1970s textbook on microbiology counseled students:

The fact that *Sulfolobus* and *Thermoplasma* have similar lipids [in their cell membranes] is of interest, but almost certainly this can be explained by convergent evolution. This hypothesis is strengthened by the fact that *Halobacterium*, another quite different organism, also has lipids similar to the acidophilic thermophiles. (Brock, 1978, p 178)

Biologists now recognize that the lipids in the cell membranes of these “bacteria” (all of which are archaea) represented a biological anomaly (*vis-à-vis* the prokaryote-eukaryote evolutionary paradigm), telling evidence that these microorganisms differ from other prokaryotes (bacteria) in an important way. As the quote underscores, however, they were not viewed in this way; they were interpreted as readily explicable in terms of convergent evolution.

Most puzzling scientific findings do not give rise to major discoveries such as ribozymes and Archaea. Ingenuity and hard work eventually resolve them within the context of widely accepted scientific beliefs. On the other hand, as the cases just canvassed illustrate, major scientific discoveries often begin with findings that resist efforts to explain them within a prevailing theoretical framework. The challenge is recognizing such phenomena for what they represent. In the case of extraterrestrial microbes, the risk that they will be misinterpreted as manifestations of poorly understood abiological processes is especially great because they may exhibit characteristics erroneously thought to be associated only with nonliving systems. They may also fail to exhibit characteristics universal to Earth life that, unbeknownst to biologists, are contingent upon conditions present on early Earth. As discussed below, the use of tentative (*vs.* defining) criteria is designed to reduce these risks.

3. Using Tentative Criteria to Search for Potentially Biological Anomalies

The purpose of tentative criteria is not (like that of defining criteria) to provide a decision procedure for estimating the likelihood that an extraterrestrial phenomenon is the product of life. Instead, it is to draw scientific attention to extraterrestrial phenomena that fail to conform to our Earth-centric presuppositions about life and nonlife in baffling and unanticipated ways. For these are the phenomena which hold forth the greatest promise of revealing a truly novel form of life and yet also run the greatest risk of being classified as just another mysterious, abiological, extraterrestrial phenomenon. In short, the purpose of tentative criteria is to screen an extraterrestrial environment for *potentially* biological anomalies (*vis-à-vis* our current concept of life).

Unlike defining criteria, tentative criteria for life are defensible, that is, open to revision and even rejection in light of empirical discoveries and new theoretical developments. Purportedly fundamental characteristics of life should be included as tentative criteria and deployed together in screening an extraterrestrial environment for biologically promising anomalies, independently of the question of which characteristic is thought to be more basic to life. This strategy decreases the likelihood that a truly novel form of life will be overlooked because it fails to satisfy a criterion

that is mistakenly thought—on the basis of our limited, Earth-centric, experience with life—to be fundamental to life; the inclusion of criteria that would otherwise be excluded (on rival definitional approaches) increases the likelihood that the phenomenon will register as having intriguingly “life-like” properties.

In addition to supposedly fundamental characteristics of life, tentative criteria should include characteristics which while not viewed as “essential” to life are nonetheless universally found in association with Earth life. Characteristics of this sort are already under consideration for use as “biosignatures” in life-detection missions. In a discussion of the upcoming ExoMars Mission, scheduled for 2020, Vago *et al.* (2017) canvass a wide variety of potential biosignatures that might prove useful for searching for martian life. The biomolecules of familiar life, for example, are built from small subsets of classes of chemically similar organic molecules; Chris McKay (2004) dubs this the “Lego Principle.” As an illustration, the proteins of familiar life are synthesized from just 20 L-amino acids even though natural processes produce over 100 amino acids of mixed chirality. Accordingly, a mysterious enrichment in a small subset of homochiral amino acids, regardless of whether they are the same as those used by familiar life, is suggestive (but not definitive) of biology. Such an enrichment cannot be viewed as definitive of life because there may be as-yet poorly understood, nonliving processes that produce similar enrichment under conditions very different from those found on Earth.

Other potentially promising candidates, discussed by Vago and colleagues, for tentative criteria for life involve contingent (non-universal) ways in which organisms found in certain conditions directly modify their environments. As an illustration, many microorganisms exhibit a tendency to form communitarian structures, such as biofilms. For this reason, Frances Westall (2008) recommends looking for microbially induced sedimentary structures (such as stromatolites) on Mars, which are easier to detect than solitary microbes or their fossil remnants. Whether microbes on other worlds would build similar structures under “analogous” conditions is unclear, however, in part because conditions on another world will inevitably differ from those on Earth in ways that may (unbeknownst to us) be relevant, and in part because many microorganisms on Earth are planktonic and do not build such structures. But this doesn’t undermine Westall’s point that finding such structures under the pertinent geological conditions—conditions resembling those in which such structures are found on Earth—would be suggestive of biology.

Living things affect their environments in indirect ways, extracting chemicals and energy for use in biological processes and releasing chemicals as waste products. A salient illustration is the persistence of oxygen and methane in Earth’s atmosphere and oceans. Oxygen and methane are reactive gases which would disappear if they weren’t constantly replenished by the metabolic activity of living things, most notably, microorganisms. The banded iron formations, which became abundant around 2.45 billion years ago, mark the “great oxygenation event” (Canfield, 2005), in which cyanobacteria became so common that they changed the chemical composition of the atmosphere and oceans, producing extensive deposits of oxidized minerals, such as he-

matite. As Hazen *et al.* (2008) counsel, evidence of extensive alteration of minerals by reactive gases is (in general) a promising biosignature for past life. Along the same lines, the persistence of otherwise inexplicable quantities of reactive gases, including but not limited to oxygen and methane, in a planetary body raises the question of whether it hosts extant life. As a number of researchers have pointed out, however, there are environmental contexts in which abiotic processes could sustain suspiciously high levels of oxygen, methane, and other allegedly biogenic gases in a planetary atmosphere (*e.g.*, Seager, 2014; Meadows *et al.*, 2017), which underscores the earlier point about the importance of tailoring a suite of biosignatures to the type of environment being explored for potential evidence of biology.

The examples canvassed above are just a snapshot of the diverse characteristics associated with familiar life that have been proposed thus far for use as biosignatures in life-detection missions. The challenge, as Vago and colleagues note, is selecting a small subset of promising biosignatures (out of a very large pool of candidates) for screening a specific extraterrestrial environment for evidence of biology. The need to tailor a suite of biosignatures to the particular environment being explored highlights the limitations of a definitional (one-size-fits-all) approach (based on allegedly fundamental properties of life) to searching for extraterrestrial life.

It is important to distinguish searching for life *per se* from searching for phenomena that *resist* classification as living or nonliving (*i.e.*, for potentially biological anomalies). A good illustration of the former approach is Vago and colleagues (2017) discussion of how to use biosignatures in the upcoming ExoMars mission to search for life on Mars. They ask “[i]s there a pragmatic set of robust measurements that could provide proof of life? Better yet, can we devise a scale or scoring system to help us quantify how confident (or otherwise) we have a right to be” (p 482). Their focus, like that of others involved in the search for extraterrestrial life, for example, Cady and Noffke (2009), is on formulating a decision procedure for deciding whether an extraterrestrial phenomenon is or (barring that) is *likely to be* life. But because *potentially* biological anomalies straddle the borderland between our concept of what it is to be a living system and our concept of what it is to be a nonliving system, one cannot assign a useful probability of life to them. From an Earth-centric perspective, such phenomena defy classification as “living” or “nonliving.” In keeping with Carl Sagan’s oft-quoted remark—“Extraordinary claims require extraordinary evidence”—they are more likely to be classified as just another poorly understood abiological phenomenon as a potential candidate for novel life. In this context, it is worth keeping in mind that truly novel, nonliving, geochemical processes, exhibiting intriguingly lifelike properties, are just as “extraordinary,” from a scientific point of view, as truly novel forms of life exhibiting nonlife-like properties. The strategy being proposed is designed to focus attention on the *biologically most promising* systems of this sort for purposes of more exhaustive investigation tailored to their uniquely baffling geochemical peculiarities.

Vago and colleagues’ selection of biosignatures for the ExoMars mission reflects Earth-centric assumptions about which characteristics of familiar life are likely to be generalizable to life on Mars. It is difficult, but not impossible,

to design tentative criteria for searching for life in environments that are extremely different from those found on Earth. As an illustration, Chris McKay (2016) postulates that *if* there is life on Titan it will be carbon-based and have biological structures (membranes, enzymes, information molecules, etc.) resembling familiar life in their bio-functionality. From McKay's perspective, the challenge is figuring out how biostructures *functionally* resembling those of familiar Earth life could be synthesized in liquid methane and ethane (as opposed to water) and what sorts of chemical traces they are likely to leave in the environment. In this context, McKay (*see also* McKay and Smith 2005) speculates that life on Titan is likely to consume hydrogen, acetylene, and ethane, and hence evidence of an otherwise inexplicable depletion of these chemicals would be suggestive of novel life. Intriguingly, computer simulations indicate that there might be a mysterious hydrogen flux from the atmosphere of Titan into its surface (Strobel, 2010). As McKay discusses, not enough is yet known to conclude that the hydrogen flux is real, let alone the product of alien biology (McKay, 2016, p 11). Nevertheless, if the phenomenon is real, then it represents a good candidate for a potentially biological anomaly and hence is worthy (on theoretical grounds) of further astrobiological investigation. It is very rare, however, for an anomaly to be anticipated before it is encountered.

A search for potentially biological anomalies is a search for phenomena that “shouldn't be there” given our current, Earth-centric, understanding of both biological and abiological phenomena. Characteristics that are rarely found among familiar organisms—that are unique to organisms found only in certain types of environments—but also seldom found in association with nonliving phenomena make promising candidates for tentative criteria “for life” in analogous extraterrestrial environments. For such characteristics stand out against the backdrop of abiological processes.

The chains of tiny magnetite crystals found inside magnetotactic bacteria provide a salient illustration. Magnetotactic bacteria live in aerobic and anoxic transition zones found in boggy environments. They manufacture tiny magnetite crystals, which they use as compasses to help them stay within these zones by orienting along the Earth's magnetic field. In addition to being aligned in chains, these tiny magnetite crystals have some very unique properties, including chemical purity and uniformity in size and shape. Magnetite crystals having these characteristics are interpreted as microfossils (the remains of magnetotactic bacteria) when found in ancient Earth rocks (Kopp and Kirschvink, 2008). It is thus hardly surprising that the discovery of tiny magnetite crystals with similar characteristics (chemical purity and uniformity in size and shape) in a meteorite (ALH84001) found in Antarctica and known to have originated on Mars was heralded by some researchers, in conjunction with other tantalizing structural and chemical features in the meteorite, as evidence that it might contain fossilized martian microorganisms (McKay *et al.*, 1996; Thomas-Keprta *et al.*, 2001). Evidence that minerals associated with these magnetite crystals had been altered by water around 3.9 billion years ago, a time when Mars is thought to have been warm and wet, played a central role in their reasoning.

The conjecture that the magnetite crystals in ALH84001 were produced by ancient martian microbes is currently rejected by most (but not all) astrobiologists. Magnetite

crystals allegedly similar in chemical purity and size and shape have been produced inorganically under conditions analogous to those undergone by ALH84001; *see* Golden *et al.* (2001), Barber and Scott (2002), and Bell (2007). But this doesn't alter the central point: Any characteristic unique to a variety of Earth life found in a certain type of environment provides a promising tentative criterion for searching for life in an analogous extraterrestrial environment until there is evidence that it doesn't. At the time of their discovery, the magnetite crystals found in ALH84001 represented a biologically promising anomaly.

Tentative criteria differ from defining criteria for life in being revisable. Their identity as well as weighting may change over time in light of new empirical discoveries and theoretical developments. Evidence that magnetite crystals resembling those found in magnetotactic bacteria can be produced abiotically under the pertinent geochemical conditions provides a salient illustration. Likewise, researchers have identified conditions under which abiological processes sustain seemingly suspicious (from an Earth-centric perspective) quantities of a reactive gas, such as oxygen, in the atmosphere or oceans of a planetary body (*e.g.*, Meadows *et al.*, 2017). But this doesn't mean that the persistence of reactive gases or presence of magnetite crystals never provides useful tentative criteria for life. The key is to distinguish conditions under which the persistence of a reactive gas in an atmosphere-ocean system or other characteristics of tiny magnetite crystals (*e.g.*, being found in credible chain-like alignments) are especially difficult to explain abiotically and to design search strategies based upon such refinements. There isn't a one-size-fits-all set of tentative criteria for searching for extraterrestrial life. Each set of criteria must be tailored to the distinctive geochemical makeup of the extraterrestrial environment being screened for anomalies having a suspiciously biological character. As Seager and colleagues counsel, “habitability is planet-specific” (Seager *et al.*, 2016, p 466).

Satisfaction of a tentative criterion for life is rarely sufficient to render a puzzling extraterrestrial phenomenon anomalous enough to be worthy of further investigation. Tentative criteria should be deployed together, as a set, to detect phenomena exhibiting a *puzzling combination* of seemingly biological and abiological characteristics. If a geochemical system satisfies “enough” tentative criteria, it will qualify as sufficiently anomalous to be worthy of investigation for an unfamiliar biology. In some cases, such as the magnetite crystals found inside bacteria-shaped structures in ALH84001, the anomalous character of an extraterrestrial phenomenon may be fairly obvious. Other cases may require considered judgement as to whether a mixture of seemingly biological and nonbiological characteristics is sufficiently mysterious to be worthy of further investigation for the possibility of alien life.

As underscored by the illustrations in the last section, anomalies typically defy our expectations in *unanticipated* ways. This makes it difficult to design a decision procedure for recognizing them in advance of actually encountering them. The results of the Viking mission's Labeled Release (LR) experiment, which were baffling, suggestive of both life and nonlife, provide an especially salient illustration of the difference between searching for alien life and searching for biologically promising anomalies. The LR biology experiment used a carbohydrate solution radioactively labeled

with ^{14}C which was known to be metabolizable by a wide variety of cultivatable bacteria; see Schuerger and Clark (2008) for a review of the Viking biology experiments and a history of the debate over the results. If there were microbes in the martian soil, the LR team conjectured that they would behave like these bacteria and metabolize some of the organic compounds in the nutrient solution, releasing radioactively labeled $^{14}\text{CO}_2$ gas in the process. Pre-mission tests of the LR procedures showed that it could detect as few as 10–12 bacteria per milliliter within 1–3 h (Levin, 1963). The LR team got the results they hoped for. Significant quantities of $^{14}\text{CO}_2$ gas were released. When a controlled experiment was performed, involving heating martian soil up to 160°C for 3 h, at a temperature high enough to kill any known bacteria, and then injecting it with a second helping of nutrient solution, $^{14}\text{CO}_2$ gas failed to be released. These responses are classically biological and hence provided strong evidence of biological activity. The principal investigators of the experiment, Gilbert Levin and Patricia Straat, were convinced that they had discovered martian life (Levin and Straat, 1976, 1977, 1979; Levin, 1997).

But when the LR team decided to give a second injection of nutrients to a sample of martian soil, anticipating that now-hungry martian microbes would metabolize it and release more $^{14}\text{CO}_2$ gas into the test chamber, the results were mystifying and completely unanticipated. Not only was no new gas released, around 30% of the gas released during the first injection disappeared from the chamber (Levin and Straat, 1977). No one had anticipated such a response. It was difficult to explain biologically or abiotically. In short, the LR experiment produced results that resemble familiar life in anticipated ways (the initial release of $^{14}\text{CO}_2$ gas and the failure to release it after heat sterilization of the soil) and also differ from it in baffling ways (the failure to release more $^{14}\text{CO}_2$ after a second injection and the unanticipated disappearance of a significant fraction of the gas released after the first injection). To cut a long story short, the LR experiment yielded an anomaly that is potentially (but not certainly) biological.

Yet this is not how the results of the LR experiment were interpreted by the parties involved. Levin and Straat insisted that they had found life on the grounds that the LR experiment “met the established criteria for the detection of living microbes” (Levin, 1997, p 146). In effect, they treated the criteria as defining. Harold Klein, the team leader for the Viking biology experiments, along with the majority of the rest of the team, concluded that they hadn’t found life and that the best explanation for the mysterious results of the LR experiment was an inorganic oxidant (Klein, 1978, 1991). Their conclusion was heavily influenced by the Viking gas chromatograph–mass spectrometer’s failure to detect any organic molecules in the martian soil (Biemann *et al.*, 1976; Biemann and Lavoie, 1979). The results of the Viking gas chromatograph–mass spectrometer (GCMS) are problematic for a number of reasons, however, including that it was so insensitive that it wouldn’t have detected as many as 10^6 microbes per gram of soil, more microbes than found in some samples of Antarctic soil (Glavin *et al.*, 2001; Navarro-González *et al.*, 2006). The important point, for purposes of this discussion, however, is that the astrobiology community quickly decided that they hadn’t found life and focused on searching for an abiological explanation—an inorganic oxidant—for the mysterious results of the LR experiment.

If the mysterious results of the LR experiment had been investigated in the manner being recommended in this essay—as a potentially biological anomaly, as opposed to in a definition-like (“thumbs up” or “thumbs down”) manner—the possibility of a biological explanation would have been pursued just as seriously as an abiotic explanation; after all, life is an oxidant.

4. Concluding Thoughts

Treating criteria for screening an extraterrestrial environment for life as tentative (vs. defining) and focusing on identifying biologically promising anomalies, as opposed to life per se, has significant advantages. On a definition-based approach, a decision procedure will assign very low odds to the most baffling anomalies—those departing most radically from our Earth-centric ideas about life—and yet these are the most promising candidates for truly novel forms of life. On the approach being recommended, in contrast, this is much less likely to happen. The search will be focused more broadly on identifying phenomena that are anomalous in puzzling ways that resist classification as biological or nonbiological. This increases the likelihood that astrobiologists will investigate forms of life differing from our own in poorly understood ways, as opposed to writing them off as just another inadequately understood abiotic phenomenon. Moreover, the former approach should do just as well as a decision procedure based on defining criteria when it comes to finding microbes resembling those with which we are familiar. For such microbes will satisfy most (if not all) of the most heavily weighted tentative criteria for life.

There is a psychological disadvantage to the strategy for searching for extraterrestrial life recommended in this essay: It is unlikely to provide a rapid and decisive answer to the question of whether a puzzling phenomenon encountered on another world is the product of biology; indeed, I suspect that the desire for such an answer explains the appeal of a definition of life and defining criteria. But as we have seen, the promise of defining criteria is illusory, especially for phenomena that defy ready classification as living or nonliving. Besides, insofar as familiar life represents a single example that may well be unrepresentative of life in as yet poorly understood or even unknown ways, it seems naïve to expect that one could quickly decide such an issue. Shouldn’t the greatest concern of astrobiologists be avoiding misidentifying a novel form of life as just another poorly understood abiological phenomenon? For until we have a better idea of the ways in which life elsewhere in the Universe resembles and fails to resemble our own, we will be unable to determine which characteristics of familiar life are fundamental to all of life, wherever and whenever it may be found, and which are contingent upon conditions obtaining at the time and place that life arose on early Earth.

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