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1 Visions of the Living Cosmos

Deep sky surveys performed by the Hubble Space Telescope in 2016 revealed that the observable universe contains upward of 2 trillion galaxies, each containing anywhere from millions to hundreds of trillions of stars. These are truly staggering numbers that make even astronomically improbable events inevitable over the vastness of space and time. Even if life is a vanishingly rare phenomenon, in a universe that is brimming with trillions of galaxies and which may, in fact, be infinite, we can expect that familiar forms of life, and perhaps many forms we could never even dream of, will emerge in the cosmos from time to time. The notion that there is an infinite number of extraterrestrial civilizations in an infinite universe is irrelevant, of course, to the practical search for extraterrestrial intelligence (SETI), which is confined to areas of the cosmos that are amenable to empirical investigation. The key issue, therefore, is not whether we are alone in the universe, but how common we should expect our cosmic companions to be and whether there is anything biologically meaningful we can say about them from our blinkered vantage point on Earth.

The question "Are we alone in the universe?"—which motivates the SETI search—is reflexively ambiguous. It could refer to we as intelligent technological civilizations, we as morphological humanoids, we as conscious critters, we as animals with vertebrae, we as complex multicellular organisms, or simply we as living things. To the extent that the concept "we" presupposes higher cognitive properties like self-awareness and social identity, the question may be pondering the prevalence of other complexly cognitive "we's" in the universe. Of course, we cannot even begin to estimate the astrobiological frequency of mindful creatures like ourselves without first considering the ubiquity of life and its basic organizational forms in the cosmological horizon.

Thinking about the prospect and nature of life in the universe is important for reasons quite apart from our pursuit of cosmic companionship. It is only by understanding the cosmic diversity—and uniformity—of biological forms and functions that we can judge whether the project of a universal biology will

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succeed. And the success or failure of universal biology has implications for the epistemic status of biological science itself. To establish biology as a truly law-like, rather than fundamentally historical, discipline, we must identify contentful evolutionary outcomes that can reliably be projected onto other life worlds, and distinguish these law-like features of life from the quirky historical results of earthly evolution. A central aim of this book is to outline a conceptual framework for separating law-like from accidental features of the evolutionary process and to apply this framework to the various possible senses of "we" that are packed into the SETI-motivating refrain.

1. The Cosmic Imperative of Life

Let us begin this grand disambiguation project, as evolution does, with the small and simple. There is a consensus building among the ranks of astrobiologists that the evolution of simple microbial life is probably common in the universe, with some going so far as to call it a "cosmic imperative."[1] As microbiological theorists will be quick to point out, however, prokaryotic (bacteria-grade) life is anything but simple, and its relevance to the evolution of complex multicellular life goes far beyond merely providing a necessary stepping stone on the evolutionary road to an intelligent *we*. The metabolic machinery of the microbial world powers the biogeochemical cycles that sustain all life on the planet, and as we shall see later, made transitions to higher levels of organization possible at critical junctures in the history of life.

1.1 On Lacunae and Laws

Let us refer to the proposition that basic microbial life is ubiquitous in the universe as the "cosmic imperative of life thesis." This thesis hangs on the law-like nature of the mechanisms and processes that produced terrestrial prokaryotes. Unfortunately, there remain yawning gaps in our theoretical understanding of the origin of life and its drivers. There is, for instance, a great lacuna between our knowledge of the origins of nucleic acids—the chemical building blocks that comprise the informational backbone of life's replication machinery—on the one hand, and the configuration of the first proper cell equipped with biosynthetic membrane and metabolism, on the other. How we got from a postulated "RNA world" to encoded protein synthesis remains, in the words of one preeminent microbiologist, "the most challenging and important problem the field of Biology has ever faced."[2]

There is currently no consensus among origin of life researchers as to whether replicating molecules or metabolizing units arose first; whether

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prokaryote cells originated once or multiple times independently in Eubacteria and Archaea (the two prokaryote domains); or even, more strikingly, whether the last universal common ancestor of life on Earth (LUCA) was phenotypically bacteria-like or rather a complex eukaryote-like cell that repeatedly gave rise to the simpler, more streamlined prokaryote lineages that exist today.[3] If the notion that LUCA was more, rather than less, complex than extant prokaryotes seems deeply counterintuitive, it is probably because it flies in the face of the "simple to complex" narrative of macroevolution in which most students of biology have been steeped. It may turn out, however, that losses of biological complexity are just as important and pervasive as complexity gains,[4] and there could even be a rough "law of conservation of complexity" operating in the formation of more complex, higher-level evolutionary individuals (see the coda to part I).[5]

Another major unresolved issue concerns the place of Eukaryota—the group that includes animals, plants, fungi, algae, and protists—within the tree of life. The preponderance of evidence now suggests that eukaryotes are more closely related to Archaea bacteria than they are to Eubacteria, having arisen from within the Archaea domain after its split from Eubacteria. This picture is further complicated by the subsequent endosymbiotic acquisition by an archean of the ancestral eubacterium that would eventually become the mitochondrion organelle of eukaryotes. If eukaryotes are essentially a peculiar branch of Archaea, then the term "prokaryote" (like the far more problematic term "microbe") is essentially a phenetic (or property-based) classification, rather than a genealogical one. That is, it picks out a morphological "grade" rather than a proper "clade" (the latter is the central unit of modern taxonomic classification, which includes a single ancestor and all of its descendants). Grade-based classifications are controversial, as they are vulnerable to the charge of subjectivity and could obscure evolutionary relationships.[6]

A further impediment to resolving the largest branches of the tree of life stems from the ubiquity of horizontal gene exchange. Prokaryotes do not have sex, but they can exchange genes through several ancient mechanisms, and this exchange can take place between very distant lineages of life. There has been far more horizontal gene transfer between bacteria, archaea, and even eukaryotes than had initially been imagined, blurring tidy Darwinian lines of descent with modification. The horizontal exchange of genetic elements across distant lineages is accomplished through viruses, plasmids, transposons, and other mobile genetic elements, and is now thought to be a central mode of evolutionary innovation in prokaryotes (and to far lesser extent in eukaryotes). As we shall see, the ubiquity of horizontal gene exchange, particularly in the earliest phases of life on Earth, significantly clouds our picture of life's origin(s).

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Despite these lingering lacunae in our understanding of the origin of life on Earth, the prevailing scientific view (or hunch) is that the emergence of prokaryote-grade life is nomically expectable, or the reliable outcome of natural laws and mechanisms, even if our understanding of these laws and mechanisms is presently incomplete. The commonly accepted idea is that there is a high probability of life emerging when particular generic conditions obtain, due to certain lawful connections. How might the existence of such lawful connections be inferred?

The now flourishing field of astrobiology was long pejoratively characterized as a science without a subject matter. It is true that there are as of yet no observations of extraterrestrials, not even of the basic microbial variety, from which we can draw generalizations about life writ cosmically large. But this does not mean that we are completely in the dark about the prospects of life on other worlds. The cosmic imperative of life is supported by several mutually informing lines of evidence. One is the observation that the basic chemical building blocks of life are readily generated under simple conditions, from which it is inferred that the molecular basis of life as we know it is pervasive in the universe. The biochemical molecules that are critical to life—such as the amino acids that make up proteins and the nucleobases that comprise DNA and RNA—can be created in the laboratory under fairly generic conditions. More recent analyses of carbon-rich meteorites, as well as spectroscopic studies of the solar system, confirm that amino acids and nucleobases are pervasive in the universe and likely deliverable by asteroid impact.[7]

Likewise, aqueous chemistry, which is often thought to be necessary for metabolism and hence the evolution of life, has also been shown to exist throughout the solar system in water, ammonia–water combination, and hydrocarbon forms. Water ice is ubiquitous, and liquid water—including oceans—have been found to have existed, or to currently exist, on many planets, minor planets, and moons in our solar system, where they are prevented from freezing by solar or geothermal energy (such as tidal flexing, radiogenic heating, or other forms of hydrothermal activity that drive plate tectonics and similar forces). This indicates that, at least in terms of its basic molecular substrate, the evolution of life on Earth did not depend on an exotic cocktail of chemical conditions that are unlikely to be replicated in the cosmos.

Nevertheless, as noted previously, there is a major explanatory gap between the origins of the basic building blocks of life, and the emergence of replicating, membrane-bound, homeostatic systems of the sort that configured the first proper organisms on Earth. Absent a thorough understanding of this transition, how can we be confident that the emergence of life is not a profoundly unlikely

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accident or even a one-off event in our galaxy or cosmic horizon? The strongest evidence for the cosmic imperative of life thesis can be found not out in the cosmos, but right here at home in the fossil record of life on Earth.

1.2 The Timing and Likelihood of Life's Origin

As with comedy, the key to the cosmic imperative of life thesis is timing. Bacterial life forms appear in the fossil record immediately after the Earth cooled from numerous world-sterilizing impacts that took place during the formation of the solar system. Layered structures called "stromatolites," which are produced by communities of cyanobacteria (traditionally referred to as "blue-green algae"), have been found in the oldest sedimentary rocks on Earth that retain fossil signatures.[8] These accretionary structures were left by sophisticated organisms that already possessed exquisite photosynthetic adaptations, which indicates that LUCA emerged much earlier than the observed fossil signatures. Filamentous bacteria-like fossils have been found in rocks associated with submarine hydrothermal vents that may be as old as 4.28 billion years, which suggests that life emerged as soon as the oceans formed.[9] Life is increasingly thought to have originated around hydrothermal vents, which offer pockets of far-from-equilibrium chemistry that are protected from surface impacts and are probably ubiquitous in the universe.[10] If the earliest life-forms on Earth are found around deep-sea vents, this would seem to rule out "panspermia"—the thesis that life originated elsewhere (perhaps on a much longer timescale) and was transported to the nascent Earth via asteroid or comet.

These findings are consistent with "molecular clock" analyses dating LUCA to the Hadean Eon, more than 4 billion years ago.[11] This pushes back the origin of life to just before a period in the Earth's history known as the "late heavy bombardment" (approximately 3.9 billion years ago). During this spike in Earth-crossing asteroid impacts, the Earth's crust is thought to have been repeatedly sterilized several kilometers deep by gigantic asteroid collisions and the fiery rain of their impact ejecta. Models indicate that life could have survived during the late heavy bombardment in protected pockets (refugia) of the geophysical habitable zone, especially in deep-sea hydrothermal vents.[12] In sum, we can say with some confidence that life arose as soon as minimally suitable conditions obtained on Earth, and that it did so despite the presence of literally hellish conditions long thought to preclude its emergence. Life appears to be a robust, not precarious, phenomenon.

Carl Sagan exclaimed that "the origin of life must be a highly probable circumstance; as soon as conditions permit, up it pops."[13] The rapid timing of life's origin does seem, at least intuitively, to support the cosmic imperative

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of life thesis over what we might call the "cosmic accident hypothesis." One way to gloss the logic of this intuition is in terms of a "likelihood" argument. According to likelihood arguments, some observation O confirms hypothesis H1 over rival and mutually exclusive hypothesis H2 only if the probability of O is greater given that H1 is true than it is given that H2 is true. Likelihood analyses view evidence as inherently contrastive: observations do not support hypotheses *simplicter*; rather, they favor one hypothesis as against another. From this perspective, confirmation is a three-place favoring relation among an observation and two rival hypotheses.

A likelihood argument for the cosmic imperative of life thesis might go something like this: the probability that we would observe basic microbial life emerge just when the Earth had cooled sufficiently to support liquid water and by implication biological functions that rely on aqueous chemistry (O_{TIMING}) is higher given that the cosmic imperative thesis (H1) is true than it is given that the cosmic accident hypothesis is true (H2). According to H1, life emerges reliably wherever certain generic conditions obtain. Although H1 does not provide a specific timeline for the origin of life, we might expect life to emerge with relative geological rapidity wherever suitable conditions arise, just as stars and planets reliably form (typically on the order of 1 million to 10 million years) given certain concentrations of matter and the absence of disrupting forces. And this is precisely what we observe: life's origin coincides with the emergence of life-friendly environments on Earth, as determined by independently supported observations and auxiliary hypotheses that allow us to pinpoint the timing of life's origin and the prevailing conditions on Earth at the time.

By contrast, the cosmic accident hypothesis (H2) does not make any particular predictions about when or under what conditions we should expect life to arise. According to this view, life is the astronomically unlikely product of a series of complexly configured causes that are unlikely to be replicated on Earth or elsewhere. Although O_{TIMING} is nomically consistent with H2, it does not relationally confirm H2. To the contrary, O_{TIMING} makes H2 less likely to be true than its mutually exclusive rival H1. For either H2 is true and O_{TIMING} is a remarkable coincidence, given all the potential values that it could have taken; or H1 is true and O_{TIMING} is a nomically constrained expectation. Our intuitions are therefore vindicated: O_{TIMING} favors H1 over H2.

On the other hand, had we observed a substantial delay between the existence of hospitable conditions and the emergence of the first microbes on Earth—such as a temporal lag on the order of billions of years—this might raise serious questions about the cosmic imperative of life thesis, particularly given that the habitability window for Earth-like planets orbiting Sun-like stars may total around 5 billion years.[14] This last point is important because it brings to the fore

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an implicit auxiliary hypothesis (A1) that is crucial to adjudicating the cosmic imperative of life thesis: namely, that the life cycles of Sun-like stars, and the ability of planets to sustain atmospheres via geothermal activity (even when they are located round a long-lived, red-dwarf star), pose outer boundaries with respect to how long the emergence of life can (on average) take and yet still be cosmically ubiquitous.

To illustrate this point, let us distinguish a further hypothesis (H3), which holds that life emerges reliably due to certain law-like connections but requires many billions of years on average to do so. The conjunction of H3 and A1 does not support the cosmic ubiquity of life thesis, due to solar and geophysical constraints on the window of habitability. However, once again, it would be an incredible coincidence for life to emerge right when favorable conditions prevailed, as predicted by H1, as opposed to anytime later in the many-billion-year time frame for its initiation as predicted by H3. Although H3 is consistent with O_{TIMING}, it is, like H2, comparatively disfavored by O_{TIMING} in relation to H1; and so O_{TIMING} relationally confirms H1 over H3, as well.

Some important complications are introduced by observer selection effects. For example, say it were the case that the only histories of life that produce beings who can reflect on these heady questions are those histories that initiate rapidly, because moderate to late initiations do not provide enough time for robustly cognitive and cultural species to emerge. In that case, O_{TIMING} would not support H1 over H2 or H3, but neither would it support H2 or H3 over H1. But let us bracket observer selection effects until later in this chapter.

1.3 The Single Origin Anomaly

There is one glaring observation that sits rather uneasily with the cosmic imperative of life thesis, however. And that is the well-supported inference, based on comparative genomic data, that all known life on Earth shares a single common ancestor, which possessed the specific genetic code that is now universal to all life on Earth. Independent origins of life are unlikely to resolve in the morphological fossil record, so we must look to comparative molecular data—the molecular fossil record—to evaluate this possibility. The LUCA inference is based not only on the universality of the genetic code itself, but also on the finding that there is a handful of particular genes that are present in all known life on Earth. Most of these universal genes code for conserved proteins that are involved in transcription and translation machinery.[15]

The origin of cellular membranes, which enclose replicating machinery into compartments and contain energy-gathering redox reactions, is somewhat hazier. Unlike the universal genetic code, it is plausible and perhaps even likely that membranes have multiple origins. The basis of this conclusion is that membrane

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lipid structure and biogenesis is radically different between Eubacteria and Archaea—so different, in fact, that archean membranes are unlikely to be derived from eubacterial ones. This offers strong evidence for the independent evolutionary origins of true cells. And if it is right, it implies that LUCA was not a free-living cell with a biogenic membrane—rather, it must have existed within inorganic, geologically created compartments that permitted replication and metabolism by preventing the diffusion of chemical reactions into the ocean.[16] So if by the "origin of life" one means the origin of free-living protocells (i.e., cells with biogenic cell membranes), there is direct evidence that life arose more than once on Earth, which lends further support to the cosmic imperative thesis.

This may not be quite enough to dispel the LUCA anomaly, however, for it still leaves us with the single origin of complex replication machinery. Recall that if the cosmic imperative thesis is true, then we should expect life to originate with some reliability and rapidity wherever suitable conditions obtain and defeasors are absent. Even the independent origins of membranes appear limited to the earliest phases of life. Why has replication and membrane machinery not appeared over and over again during the long history of life on Earth? Because suitable conditions have been present on Earth for nearly 4 billion years, with no obvious disturbing conditions that would otherwise impede subsequent origins of life, the LUCA observation (O_{LUCA}) appears to disconfirm the cosmic imperative hypothesis (H1) relative to the cosmic accident thesis (H2). It is as though we had examined a large sample of habitable worlds with identical conditions to those on Earth and found that life never originated on any of them.

There are several problems with this line of reasoning, however. Simply put, the fact that all known life on Earth shares a single common ancestor (LUCA) does not imply that life only originated once on Earth. Life may have originated numerous times, but the descendants of those independent origins may (1) fail to be recognized as independent trees of life because they are empirically indistinguishable from the dominant tree, (2) emerge at some regular frequency but be quickly metabolically dispatched (eaten) or outcompeted by members of the dominant tree—or else go extinct for stochastic reasons that prevent them from gaining a phylogenetic foothold to the point of detection, and/or (3) exist in substantial numbers and in substantially different genetic forms but, due to their microscopic nature, have yet to be discovered. If there are good reasons to think that any of these possibilities is true, then O_{LUCA} does not favor either hypothesis over the other.

The comparative genomic data on which the O_{LUCA} inference is predicated relies on the highly plausible—but nonetheless contested—assumption that the universal genetic code is only one among a very large number of functionally

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equivalent codes that could have evolved but, for quirky historical reasons, did not actualize. In other words, the O_{LUCA} inference is only permissible against a certain background theory, namely that there are weak functional constraints on the shape that genetic codes may take—an assumption that underpins Francis Crick's "frozen accident" theory of the genetic code.[17] If, in fact, codes vary widely in their functionality—such as with respect to their mutational robustness or ability to carry information—and if a wide range of code space is accessible to selection in any given history of life (especially early on), then the same functional code is likely to evolve independently, whereas functionally suboptimal codes will tend to be driven to extinction. On this view, the known code is universal not because it is a frozen accident but because it reflects an optimal attractor in "code space."[18] If this is so, then numerous origins of genetic codes will be obscured by molecular convergence and early competitive replacements, which have left no trace of countless failed evolutionary experiments in the transmission of biological information.

Even if this view is wrong, and functional constraints on genetic codes are weak (as they are widely believed to be), the first actual code among the early codes to evolve may gain an "incumbent advantage" that precludes the evolution of alternative codes by packing the available niches. In other words, once life on Earth was pervasive, any subsequent origins of replicating molecules, as well as the resources any new life-forms would have had to compete for, would have been quickly gobbled up by the plethora of existing organisms. These voracious incumbents—descendants of the first functionally adept origin of life—would have already been well-suited to their lifeways, preventing any new functional codes from becoming established in the billions of years after LUCA. These first true cells would have had sufficient time to populate and adaptively radiate into the empty ecological landscape before any major alternative trees of life could be established.

In their seminal work on incumbent replacement, Rosenzweig and McCord noted that challengers are faced with an evolutionary catch-22: in order for an invading lineage to displace an incumbent, it must evolve the suite of fine-scale local adaptations that give it a selective edge over the incumbent.[19] The catch, however, is that selection can only produce this suite of adaptations in the local environment that is currently dominated by the incumbent. Thus, selection cannot produce superior adaptations until the invader displaces the incumbent; but it cannot displace the incumbent without the superior suite of traits that it needs to succeed in the incumbent's niche. It stands to reason, therefore, that absent some separate extinction event that weakens or knocks out the incumbent, incumbent species are safe in their niches.

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Any incumbent advantage that did belong to the first prokaryote tree of life would have been massively accentuated by the exchange of "public biological goods" through lateral gene transfer, which appears to have dominated the initial evolutionary phases of life on Earth.[20] Recent modeling work by microbiologist Carl Woese and his collaborators suggests that lateral gene transfer within communal innovation pools will tend to drive a single genetic code to fixation. Their argument runs as follows. Lateral gene transfer, a major source of innovation and evolvability in prokaryotes, can only occur if there are sufficient levels of code similarity between sharing lineages. As a result, lineages with "alien" codes that were very different from the incumbent code would have been at a severe evolutionary disadvantage because they would have been unable to avail themselves of the enormous communal pool of genetic goods that was available through lateral gene exchange. This, in turn, would have denied them access to the very substantial reservoir of adaptive variation—and hence evolvability—that lateral gene-sharing affords.[21]

Their argument goes further, however. Not only would sufficiently alien codes have been driven to extinction, but in addition we should expect natural selection to bring existing alternative codes closer to one another in an evolutionary process they call "code attraction." Together, the selective purging of alien codes and the process of code attraction can be expected to result in the elimination of alternative trees of life and the fixation of a single, universal code: ergo, O_{LUCA}. It follows that even if alternative codes arose from time to time in the history of life, and even if some of these alternative codes were functionally superior to the incumbent code, they would have been precluded from gaining a foothold due to incumbent advantage and would be eliminated or convergently modified via code attraction in the rigorous competition between innovation pools. Once the incumbent code solidified and rose to dominance, an increased premium would have then been placed on fidelity of transmission, and developmental constraints would prevent any further exploration of code space. We would then be left, for the remainder of life's history, with a single code of life.

Woese's picture of communal evolution as an explanation of code universality is striking for many reasons, not the least of which is that it implies that there was no single, discrete common ancestor of all extant life. Instead, there was a single ancestral *communal population*. On this view, proper "tree-like" evolution, with clean lines of vertical descent, would not come until later in life's story. The communal ancestor model of LUCA also contrasts sharply with Crick's frozen accident theory because it offers a window for the selective optimization of the code through lateral gene exchange. But most importantly

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for present purposes, it explains away the anomaly of single origin by rendering O_{LUCA} as the nomically expectable result of prolific lateral gene exchange in the early phases of life on Earth.

In short, even if chemical conditions on Earth have been amenable to the emergence of life for billions of years, *biotic* conditions may have prevented independent life lineages from becoming established to the point of scientific detection. Even if separate prokaryote lineages have been established and remain with us, there is a good chance they will not be detected. Macroscopic life forms are far more likely to have their genomes analyzed; yet all macroscopic organisms are eukaryotes, a relatively young evolutionary branch of the incumbent tree, and thus not where we would expect to find alternative codes. Until a far greater proportion of microbial diversity is analyzed, we cannot be sure that there are no tiny aliens living among us.

Establishing a new tree of life will always be a Quixotic endeavor, given the high probability of extinction as a lineage battles away from the absorbing boundary of extinction. Stochastic (or "random walk") models of extinction and diversification suggest that only one of numerous independent origins of life can be expected to survive, if any life survives.[22] If this is right, then any history of life that is successfully established is likely to have emanated from a large number of beginnings rather than from one, even though all organisms at nearly every given time slice in that successful history of life can be traced to a single origin. In other words, any tree of life that is around long enough to permit one of its tiny twigs to read these pages will, in all likelihood, have emanated from a multiple origins scenario.

For all these reasons, the observation of code universality does not compellingly speak to a single origin of life's replicating machinery. When we take into account the evidence for an extremely early origin of life, the repeated evolution of free-living cells, the cosmic ubiquity of the chemical building blocks of life, and models of code convergence under heavy horizontal gene transfer, a strong case can be made for the cosmic imperative of life thesis, even if a single alien microbe has yet to be found. If this cosmic imperative thesis is eventually confirmed beyond a reasonable doubt, it will most likely be through sophisticated next-generation telescopes that analyze the gaseous compositions of exoplanets for the biochemical signatures of life, such as gases produced by metabolic redox reactions and other living activities. Yet even this endeavor is fraught with the risk of false positives (because geological processes can mimic living ones) and false negatives (because we may fail to recognize the diversity of metabolic forms that life can take).

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2. Extending the Cosmic Imperative: Nonbiological Approaches

If the cosmic imperative thesis for basic microbial life is on reasonably firm foundations, the case for the cosmic ubiquity of more complex forms of life is on far shakier ground. It is here that scientific views begin to diverge rather sharply along disciplinary lines, resulting in two contrasting visions of the living cosmos. Astrophysicists, especially advocates of SETI, have historically been optimistic about the possibility of complex—and complexly cognitive—life-forms emerging in a sizable fraction of cases where basic microbial life evolves. Even if this fraction is small and complex life is rare among life worlds, given that nearly all stars appear to have planetary systems, there is likely to be a staggering number of habitable planets in our galaxy.[23] Thus, the Milky Way should be teaming with complex life, as is often depicted in science fiction. Evolutionary biologists, meanwhile, for reasons that will soon be clear, have been less sanguine about such prospects.

The astrophysicist's optimism about macroscopic life in the universe has reposed on general statistical considerations, assumptions about the uniformity of nature, and extrapolation from the familiar modes of inference and explanation that are endemic to the physical sciences, rather than from any specifically biological justifications. As we shall now see, these approaches cannot take us very far toward gauging the cosmic frequency of complex life.

2.1 The Copernican Principle and Observer Selection Effects

The Copernican principle holds, in essence, that we should be suspicious of scientific theories that take humans to be special or privileged observers. The sixteenth-century Polish astronomer Nicolaus Copernicus famously showed, contrary to long-standing wisdom, that the Earth does not lie at the center of the solar system but rather revolves with numerous other planets around the Sun. Centuries later, we now know that although the Sun lies at the center of our solar system, it is in fact a mundane star located in a low-key suburb of an inconspicuous galaxy that is buried in a field of perhaps trillions of galaxies. Nothing in this picture smacks of a universe centered, literally or figuratively, around humans. As cosmologist and SETI theorist Milan Ćirković remarks, "the relentless march of Copernicanism has repeatedly threatened and destroyed our cherished myths and prejudices in the course of the last … five centuries."[24] It is only natural, therefore, to think that the notion we are the cosmic exception is merely the next mythic construction of anthropocentricism teed up for Copernican demolishment.

The Copernican principle can be read in either of two ways: one psychological, the other statistical. Read psychologically, the Copernican principle is less

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of a "principle" and more a cognitive corrective for the human predilection to interpret data in a self-centered, ad hoc, or politically motivated way so as to preserve theories or religious doctrines that secure a privileged position for humanity in the universe (such as the geocentric model of the solar system or the biological theory of special creation). The reason why this penchant for privilege is properly considered a bias is that it has led us systematically astray in the past—and thus, so goes the induction, it is likely to lead us epistemically astray in the future.

Statistical readings of the Copernican principle, such as the "mediocrity principle"[25] or "typicality principle"[26] formulations, attempt to provide a more formal justification for the directive that we ought to be wary of privilege-preserving theories. If we assume that the shape of life on Earth falls squarely within the bell curve of living worlds, then we can predict with high confidence that life on other habitable worlds will not only exist but in some cases will be highly similar to our own. This reasoning is surely flawed. Even Carl Sagan, probably the twentieth century's most prominent advocate for SETI, conceded that applying the Copernican and mediocrity principles to the question of life elsewhere in the universe is little more than an act of faith. The problem with using these principles to draw inferences about extraterrestrial life is not that they are faith based, but rather that they are distorted by observer selection effects.

No matter how infinitesimally rare the evolution of higher cognitive life may be, any intelligent observer contemplating the frequency of other we's in the universe will by necessity occupy a planet where intelligent life *did evolve*, and where it evolved *in a particular way* (e.g., where it was instantiated in a morphological humanoid form). So long as the only example of life we have is our own, it would be a grave mistake to infer on the basis of the Copernican or mediocrity principles that intelligent organisms—let alone intelligent humanoids—are likely to evolve whenever or even in a significant fraction of cases wherever life arises. We cannot infer from what did happen to what had to happen purely on the basis of statistics.

Consider the sizable,nearly 4-billion-year time lag between the origin of basic microbes and the evolution of intelligent multicellular life on Earth, a period that spans nearly one-half of the entire main sequence of the Sun. One might conclude from this observation, drawing on the mediocrity principle, that the evolution of intelligent life is a run-of-the-mill occurrence, taking place, as it did, smack dab in the middle of the Sun's main sequence. Theoretical physicist Brandon Carter argued, however, that this intuitive conclusion is misguided because it fails to take into account observer selection effects.[27] Carter reasoned this way: any being computing the average time to intelligent

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life on a planet must itself have emerged within the main sequence of its star; in other words, observer selection effects prevent any observations from occurring beyond the habitable sequence of the local star. Taking this into account, the fact that the time it took for intelligent life to emerge on Earth is close to the total duration of the habitable sequence of the Sun (within a factor of 2) suggests that the average time to intelligent life in any history of life is in fact much longer than the main sequence of Sun-like stars.

In essence, Carter argues that it is astronomically unlikely that the time it took to produce intelligent civilization on Earth just happens to be comparable to the duration of the main sequence of the Sun, because the astronomical and biointelligence timescales are not causally correlated. This observation is precisely what we should expect, taking into account observer selection effects, if the average time to intelligent civilization is much longer than the main sequence of Sun-like stars. Thus, Carter concludes that our own case is likely to represent one in which intelligent life proceeded much more rapidly than is cosmically typical.

Recent studies on the effects of solar output on the Earth's climate strengthen this conclusion by narrowing the habitable portion of the Sun's life cycle. Modeling work suggests that the Earth will become inhabitable to all but basic microbial life in less than 1 billion years due to the effects of increasing solar output on the biosphere.[28] If this is right, then the emergence of intelligent life on the very tail end of the habitable portion of the Sun's life, taking into account observer selection effects, could indicate that the average time to the emergence of intelligent life on Sun-like stars may be significantly greater than the habitable portion of their main sequence.

Carter's argument has been subject to its fair share of criticisms, and I will not say more about it here.[29] However, the SETI skepticism that flows from Carter's argument could be tempered by the recent finding that red dwarfs—very low mass stars that burn stably for trillions of years—are by far the most common type of star in our galaxy and could present a substantially greater window of habitability than main sequence stars. Yet if red dwarf stars are a hundred times more numerous than Sun-sized stars and equally habitable, then why is it that we do not hail from a red dwarf star system? These mysteries would be dissolved if it turns out, as some recent evidence suggests, that red dwarf star systems are inhospitable to life or at least to complex life. Even if red dwarf systems are habitable, their window of habitability may be comparable to that of main sequence stars due to the outer limits of geothermal processes that support aqueous oceans and molten metal cores (and hence magnetospheres, which deflect solar winds that would otherwise deplete atmospheres, as appears to have doomed the early Mars).[30]

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If we zoom out to cosmic timescales, then what looks like a late origin of intelligent life in the evolution of our *solar system* is revealed to be an incredibly early origin of intelligence in the evolution of the *universe*. Star formation is not expected to end in galaxies for at least a trillion years: why is it, then, that we hail from such an early phase in the history of the universe, rather than from a time slice in the distant future, which would appear to be millions of times more likely? As with the rapid origin of life on Earth, the timing of the origin of intelligence in the universe is not affected by observer selection biases. The fact that we hail from the first one billionth of the life of the universe as we orbit a second-generation main sequence star seems to speak in favor of the cosmic ubiquity of intelligence.

Let us return, however, to the rapid origins of life itself. On its face, the evidential value of O_{TIMING} is not undermined by observer selection effects; for while it is true that the *origin* of basic microbial life is subject to observer biases—in that any macroscopic observer will necessarily come from a planet where microscopic life has arisen (and probably many times)—the *timing* of life's origin is not. An observer could just as well hail from a history of life that took several billions of years to commence after suitable conditions arose, as it could from a history of life that got rolling right when suitable conditions obtained. This is why the rapid timing of life's origin on Earth supports the cosmic imperative thesis about the evolution of basic microbial life, whereas the enormous timespan that was required to develop complex multicellular life (about 3.5 billion years) and then, on top of that, intelligent/technological species (another 500 million years) bespeaks the comparative cosmic rarity of such outcomes.

Having said this, one could argue that there is, in fact, an observer selection effect in relation to the timing of life's origin: if it takes an exceedingly long time on average for intelligent life to arise, then intelligent observers will tend to hail from histories of life that get off to an early start, just as ours did, even if early starts are vanishingly rare. The takeaway lesson is that we must steer a careful course between deluded anthropocentrism, on the one hand, and anthropomorphic projections that neglect observer selection biases, on the other. The Copernican principle is simply too coarse-grained, too inductively unsupported, and too subject to observation selection effects to navigate these deeply biological waters. Unfortunately, as historian of science George Basalla noted, this has not stopped "virtually every commentator on the subject of extraterrestrial life, and every scientific research program seeking intelligent alien life, [from] operat[ing] upon this principle."[31]

These problems demonstrate why it so important to search for biologically specific theory and data to inform our prognostications about the prospects of

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complex life in the universe. One reason why this book is addressed to the phenomenon of convergent evolution is because, as we shall see, evolutionary iteration offers a distinctively biological source of evidence that gets around pesky observer selection effects.

2.2 The Uniformity of Nature

Physical science has generally operated on the assumption that the basic laws of nature are spatiotemporally invariant—that they hold at all times and in all places. If some sequence of events occurred one way in the past or in one region of the universe, we can presume that it will unfold in the same way in the future or in another region of the universe. The eighteenth-century titan of philosophy David Hume famously showed that the "uniformity of nature" assumption on which the method of scientific induction rests cannot be grounded in logic because it does not follow deductively and cannot be induced from past experience without vicious circularity.

Many are tempted to argue that the uniformity of nature assumption is justified because it has been borne out by the remarkable predictive and explanatory successes of science. Hume argued, however, that we cannot conclude from the past successes of the inductive method that induction will be successful in the future because there is no guarantee that the future will be governed by the same laws as the past or that one region of the universe will be governed by the same laws as another region—even though his has, thus far, been the case. Induction, moreover, cannot ground itself. We must therefore look to other, more pragmatic sources of justification for the scientific method. For instance, the philosopher of science Hans Reichenbach argued that if any method will be capable of making successful predictions, then induction will succeed; in other words, if the future is amenable to prediction, then induction will work. If the future is not amenable to prediction, then no method will work. So we have everything to gain and nothing to lose by employing the rules of induction.[32]

Several centuries of scientific observation give us good reason to believe that many physical, chemical, and geological regularities are spatiotemporally invariant—or at least we may proceed, methodologically, as if they were. So why not operate on the assumption that the same regularities that characterize Earthly biology will apply to living systems everywhere in the universe? The trouble with uncritically extending the uniformity assumption into the life sciences is twofold. First, biologists have no similar methodological or inductive base from which to justify the presupposition of uniformity. We learned from Newton that the same physical laws that govern the interaction of terrestrial objects also govern the interaction of celestial ones. In biology, however, there are no observations of extraterrestrial life against which to test the uniformity hypothesis. Whether ter-

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restrial biology can be projected onto other life worlds in the way that terrestrial physics can be projected onto the heavens remains unknown.

Second, even if the assumption of uniformity is methodologically warranted, this does not preclude many regularities in the universe from being fundamentally accidental rather than the necessary outcomes of laws. Some generic biological laws, such as the principle of natural selection, may apply to life everywhere and every-when because they amount to a priori mathematical models[33] or applications of probability theory.[34] Yet for all we know the specific biological regularities observed on Earth—from particular metabolic innovations, to the structure of the genetic code, to the morphological shape of life—are contingent accidents that result from quirky chains of events that are unlikely to be replicated on other living worlds.

In an epic illustration of the dangers of prognosticating on the limits of science, towering German philosopher Immanuel Kant infamously proclaimed from the comfort of his eighteenth-century armchair that there would never be a Newton for the blade of grass. Kant was skeptical that humans could ever explain the origins of natural ends (biological functions) without recourse to an intelligent designer. Many authors have been quick to tout Charles Darwin as precisely such a "Newton." Darwin's theory of natural selection provided an elegant mechanistic explanation of the exquisite ecological match between organisms and their environment, which Kant, in his penchant for categoricity, had proclaimed was in principle unsolvable.

Yet in an important sense Darwin was not another Newton. Newton's theory of gravitation causally unified terrestrial and celestial events that were previously regarded as disparate kinds of phenomena. Similarly, the great achievement of the Darwinian revolution—which combined the theory of natural selection with the theory of common descent—is that it unified an astounding range of observations.[35] However, unlike Newton's physical theory and its modern counterparts, the theory of natural selection does not make any specific predictions about how histories of life will unfold elsewhere in the universe, or even whether they will. The reason for this relates to the "schematic" nature of natural selection.

As philosopher of biology Robert Brandon shows, when the principle of natural selection is articulated in general form, it applies to all evolving systems in the universe; but framed in this generic manner, it makes no specific predictions about what sorts of evolutionary outcomes we can expect to occur.[36] When the theory of natural selection is framed in specific terms, such as in relation to a particular population of organisms with particular traits, genetic variations, developmental interconnections, and ecological pressures, then it admits of specific predictions—but there is no reason to think that these

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specific predictions will project to life elsewhere in the universe. The developmental and ecological details on which such predictions depend may, for all we know, be entirely accidental and thus restricted to a narrow time slice of life on Earth. This has motivated skepticism among evolutionary biologists and philosophers of science about the feasibility of developing a truly law-like science of life.

3. The Cosmic Contingency Thesis

Evolutionary biologists have long complained that committees tasked with computing the probability of intelligent extraterrestrials have tended to focus on (bio)physics and (bio)chemistry while on the whole failing to engage with evolutionary theory and data regarding large-scale patterns in the history of life on Earth. For instance, when participants of the historic Green Bank Conference in 1961 attempted to assign probabilities to factors in the (in)famous Drake equation—which attempts to quantify the probability of extraterrestrial civilizations in the galaxy—not only did they assume that intelligence will inevitably evolve on any living world, but in addition they estimated that around one in five intelligent extraterrestrial lineages would develop powerful technological civilizations with capacities for radio communication. Although these conclusions were minimally informed by work on the evolution of intelligence—such as by New Age psychoanalyst John Lilly's research on dolphin communication—no one at Green Bank was operating with a truly broadscale picture of life on Earth or an in-depth understanding of the evolutionary process. The historical lack of biotheoretical input into SETI theorizing is important because macroevolutionary science may have a very different story to tell.

3.1 The Biologist as SETI Spoilsport

To many (perhaps most) biologists, the history of life is not a linear narrative of progression toward ever more complex forms of life culminating in a single, self-aware species of hominin. Rather, macroevolution presents as a series of historically contingent events with unpredictable consequences, a pattern that provides little assurance of the evolution of complex life, let alone complexly cognitive beings like ourselves.

As macroevolutionist G. G. Simpson noted more than half a century ago, theorists with a bird's-eye perspective of life on Earth have tended to play the role of SETI spoilsport. Simpson's own SETI skepticism was motivated in part by astrophysical assumptions that have been exploded in the decades following publication of his influential "anti-SETI" manifesto.[37] For instance, we now

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know that extrasolar planets are not a rare occurrence but rather a reliable outcome of stellar system evolution—yet another instance of successful Copernicanism in action. The argument with the most staying power is Simpson's appeal to the role of contingency in evolution. Simpson contended that "even slight changes in earlier parts of the history would have profound cumulative effects on all descendent organisms through the succeeding millions of generations."[38] Accordingly, the trajectory of life on Earth represents but a tiny fraction of the possible directions, organizations, and functional morphologies that life could take. If so, then there will be few meaningful properties of the actual history of life that can be projected onto other life worlds. Let us call this view the "cosmic contingency thesis."

Echoing Simpson's trenchant criticisms of exobiology three decades earlier, the evolutionist and SETI skeptic Ernst Mayr complained in a letter to the journal *Science* that the "expert" views on which SETI grants were based are almost entirely those of astronomers, physicists, and engineers, even though the factors that will determine the success or failure of the SETI project are distinctively biological and sociological.[39] Mayr argued that the prospect of making contact with advanced extraterrestrial civilizations is too astronomically miniscule to justify supporting SETI programs with taxpayer money. He also criticized physical scientists for thinking "deterministically" about the evolution of complex life—that is, for assuming that once basic microbial life emerges, the evolutionary process will drive inexorably toward intelligence.

Other prominent students of macroevolution have followed Simpson's spoilsport model in tending toward a less sanguine view of SETI success, stressing the role of contingency, unpredictability, and unrepeatability in the great twists and turns of the history of life on Earth.[40] As the paleobiologist David Raup notes, most evolutionary biologists have been "quite negative and their views have been trotted out by the anti-SETI forces to argue for the futility of search programs, or at least for the very small probability of success."[41] Evolutionary anthropologist Jared Diamond, for example, has reinforced Simpson and Mayr's anti-SETI arguments, arguing that although certain isolated traits might be evolutionarily repeatable, the overarching lesson of macroevolution is that complex outcomes, such as the bundle of traits that comprise specific taxa, are accidental regularities limited to life on Earth.[42]

This is not to say that all evolutionary biologists have been down on the SETI project. Even some evolutionists who take contingency seriously have been SETI supporters (David Raup and Stephen Jay Gould[43] are prominent examples). Nevertheless, there are sound theoretical reasons for thinking that the evolutionary processes that produce life—and hence the epistemological character of the science that studies it—are of a fundamentally different

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character from the processes that govern and sciences that explain the dynamics of purely physical and chemical systems. Put simply, the study of species may have little in common with the study of stars. If there is a fundamental difference between these disciplines, it lies in the irreducible historicity of biology. This historical view of life is most forcefully articulated in the work of Stephen Jay Gould, whose seminal argument for evolutionary contingency will serve as the launching point for the rest of this book.

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Contingency and Convergence

Toward a Cosmic Biology of Body and Mind

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