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What Makes "Weird" Life Weird?

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Abstract. In this article, I analyze the claim that alien life could be "weird". I propose to distinguish between two types of astrobiological weirdness: a naturalistic and an epistemic one. Weirdness, naturalistically construed, is an attribute for astrobiological traits. Weirdness, epistemically construed, is an attribute for scientific hypotheses and theories about the nature of such traits.

Keywords. Weird Life, Life as We Do Not Know It, Life on Earth, Alien Biochemistry

1. Introduction

It is often said in astrobiology that extraterrestrial life could be very different from life on Earth. Alien organisms might use body plans, energy sources, or reproductive strategies unlike anything we know from Earth. Perhaps life could be based on solvents other than water. Perhaps life could exist on Jovian planets, in interstellar dust clouds, or in the interior of stars. Not all hypothetical, alternative ways of life are different in the same way. Some potential kinds of life seem more similar to life on Earth than others. Some seem quite plausible, while others sound outright fictitious.

This article discusses how to measure and classify ways in which potential, alternative forms of life may deviate from the kind of life we find on Earth. My focus will lie on the notion that life could be "weird". The scientific literature is considerably ambiguous in the way astrobiological weirdness is spelled out. I propose to distinguish between two different conceptions of weirdness: a naturalistic conception and an epistemic conception. Weirdness, naturalistically construed, is an attribute for traits possessed by organisms, taxa, ecosystems, or biospheres. Weirdness, epistemically construed, is an attribute for scientific knowledge claims that can be made about such traits. While I don't have the time to formulate an exact account for each kind of weirdness, I will sketch roughly what such accounts should have to look like in order to be scientifically useful.

2. Weird Life

The vocabulary used to describe weird kinds of life is notoriously messy. The NASA astrobiology strategy (Hays 2015) uses the label "weird life" to specifically refer to organisms and biospheres whose biochemistry is based on molecular scaffolds other than carbon and chemical solvents other than liquid water. Davies et al. (2004), on the other hand, speak of "weird life"to refer to any form of life that is biochemically different from known life on Earth, including carbon- and water-based organisms and biospheres. Worse even: In the scientific literature, we find a kaleidoscope of labels that have been used to refer to virtually any kind of way in which alien life might be biochemically or otherwise different from the kind of life we find on Earth:"life as we do not know it", "exotic life", "unfamiliar life", "life as it could be", etc.

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In order to prevent getting lost in terminological quandaries, it is useful to specify what the notion of weirdness is supposed to do. If we consult the scientific literature, we find two contrasting roles that the vocabulary of weirdness performs in astrobiological theory and practice. First of all, the vocabulary of weirdness is used as a classificatory tool to separate forms of life that are similar to the kind of life we find on Earth from genuine "alternative" forms of life. Secondly, the vocabulary of weirdness is used as a measure for the degree of dissimilarity between known life on Earth and some genuine alternative form of life. In this regard, it is often proposed that differences in the traits that make life weird translate into differences in the ability to justify scientific beliefs about weird life. NASA (Hays Ibid., 147–148) writes:

"Astrobiology has involved exhaustive study of past and present life on Earth, providing lessons that can be extrapolated to environments on other worlds. This [...] is at the heart of how we plan to search those environments for signs of Earth-like life [...]. Those who propose to search for "weird life" must start by developing viable working models of such life."

In order to identify how to search for life outside of Earth, we need models for the kind of chemistry (of organisms as well as their abiotic habitats) we are looking for. Among many other things, this includes a model of the biological and abiotic chemical pathways that produce a given chemical substance, or pattern that can be recognized. The NASA report argues that the chemical models we have to search for the signatures of life we know are not informative in determining what kind of signatures to search for that might be produced by some form of life that does not share our own biochemistry. Arguably, in order to determine what phenomena to look for, where to look for them, etc. when searching for "weird life", we therefore first need to develop "viable working models" of such forms of life. Davies et al. propose a slightly different way to analyze weirdness. Rather than a catch-all distinction between forms of life that are ordinary life and forms of life that are weird, they (Ibid, 242) argue that weirdness comes in degrees, so that some forms of life might be weirder than others:

"A fundamental obstacle in searching for life as we do not know it is that we cannot be sure what to look for. It is therefore useful to construct a hierarchy of weirdness that progressively departs in its biochemistry from standard life. [. . .]The hierarchy of increasing weirdness is paralleled by the increasing difficulty in our ability to detect that life, even if it is located in our immediate vicinity."

According to Davies et al, some form of life A is weirder than another form of life B, if A is biochemically more different than B from the kind of biochemistry we know on Earth. The larger the difference in biochemistry, the more difficult it is arguably to predict what such life will look like. While Davies et al. and Hays seem to disagree about the extent to which some hypothetical biochemistry would have to differ in order to deserve to be labeled as "weird", they share some common ideas. Two of these ideas are relevant to spell out right now. (1) Astrobiological weirdness is a naturalistic attribute: Some form of life is weird if, and only if, it is biochemically different from the kind of life we are familiar with on Earth. (2) Biochemical difference corresponds to and/or correlates with predictive difficulty: The bigger the gap between the biochemistry of weird life and familiar Earth-life, the more difficult it is to make reliable predictions about the phenomena produced by weird life. Before we can put pressure on these claims, let's spell them out more clearly.

3. Naturalistic Weirdness

Davies et al. suggest to distinguish between "Earth-life", which supposedly refers to "all life on Earth, regardless of its biochemistry", and "standard life", which refers to "life that uses the general biochemical architecture for life on Earth as it is taught in standard textbooks". Their motivation for this distinction is that it could be the case

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that some yet undiscovered "shadow" biosphere exists on Earth that does not possess the general biochemical architecture taught in standard textbooks. This is sensible: If some non-standard life was able to originate on Earth, it would be odd not to call it Earth-life. As scientists may have not been able to discover all life that ever has evolved on Earth, it also makes sense to distinguish between Earth-life per se and "known" (or "familiar" or "extant") Earth-life. Usually, known life on Earth is characterized as an evolutionary tree or web of life that can be reconstructed from the three extant domains of life – Prokarya, Archaea, and Eukarya –, which share a last universal common ancestor (LUCA) (Weiss et al. 2016). Davies et al., as we have seen, think of astrobiological weirdness as some sort of a measure for how different some instance of life is from extant Earth-life, biochemically speaking. What weirdness measures is some sort of physicochemical distance in the space of biochemical possibility: The more the biochemistry of some hypothetical or actual form of life departs from standard life, the weirder it is.

The physicochemical perspective is compelling for a number of reasons. To begin with, it allows us to use the notion of weirdness across different levels of biological hierarchy. It also incorporates ecological considerations: Cellular biochemistry is causally, structurally, and functionally linked to the physics and chemistry of the abiotic environment. The structure and function of biomolecules can change drastically if environmental conditions (pH-levels, temperature, etc.) change. What kind of biochemical traits are possible or beneficial to have for some organism or population is constrained by the physics and chemistry of its environment. Finally, the physicochemical perspective provides us with a framework for identifying the kind of traits that some form of life must have to be considered weird: Biochemical or biophysical traits that life might have instead of standard traits.

In the astrobiological literature, we find a wide variety of proposals for such traits. Among other things, this includes alternative atomic constituents (bulk elements or trace elements), energy sources and energy-harvesting mechanisms, building blocks (other sets of sugars, lipids, nucleic acids, and amino acids, or entirely different classes of molecules), chemical solvents (non-aqueous liquids) or chemical milieus (fully or partially non-liquid), habitability constraints (temperature, pressure, salinity, UV-tolerance, etc.), molecular scaffolds (inorganic polymers and the chemical pathways to synthesize them), genetic codes (e.g., alternative substrates to encode hereditary information or different codification schemes), and morphotypes (e.g., cellular boundaries other than cell walls) (Grefenstette et al. 2024).

Davies et al.'s suggestion, as we have seen, is to "construct a hierarchy of weirdness that progressively departs in its biochemistry from standard life". It's not entirely clear what such a hierarchy should look like, considering the plurality of potential non-standard traits that have been suggested. For example, some hypothetical type of cell could use standard nucleic acids (RNA and DNA) but not for self-replication and still use amino acids to store hereditary information – some sort of "protein world". Another type of cell might use nucleic acids for self-replication and amino acids to build proteins but none of the standard building blocks to build these polymers, e.g., nucleotides other than A, T, C, G, and U. Which type of cell should be considered more different from standard cells?

Davies et al.'s suggestion seems to be that the astrobiological weirdness hierarchy is not strictly speaking a continuum but a ladder: Silicon-based life might not clearly be weirder than boron-based life or sulfur-based life. But it is clearly weirder than a carbon-based biochemistry with a proteome built from non-standard amino acids would be. A ladder of weirdness makes more sense, biochemically speaking. The molecular architecture of life is an integrated whole whose parts are highly specific in the way they fit to each other and work together. There are various developmental, chemical, and physical constraints that may prevent replacement of molecular constituents with potential analogues. Some constituents might be easy to replace without substantially

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changing the rest of the cell. But others will only be possible to replace along with an entire group. You can't replace phosphate without getting rid of (standard) nucleic acids, and you can't get rid of nucleic acids without losing the genetic code. Some potential ways to build a molecular architecture will unlikely overlap in any way at all. Water and ammonia, for example, have quite different melting and freezing points, so that they cannot co-exist in the liquid phase. Water-based life and ammonia-based life (if it exists), thus, will have a considerable gap between the physicochemical conditions (e.g., pressure and temperature) under which each of them can be found (Bains 2004)

A ladder of weirdness could be potentially modeled as a hierarchy of different degrees of biochemical incompatibility. According to this view, a weird form of life would be one that is biochemically incompatible with standard life. The more strongly incompatible it is, the weirder it is. A weak sense of incompatibility could be reproductive: Roughly speaking, we can say that some hypothetical or actual form of life is reproductively weird, if it cannot evolve from standard life. This could be due to developmental constraints, constraints in the architecture of the replication system, etc. A stronger sense of incompatibility could be ecological: Roughly speaking, life is ecologically weird, if it cannot exist in the same ecological niche as standard life. These suggestions are tentative. Further specification and differentiation will be necessary. What matters for scientific theorizing and practice is to provide a coherent frame-work for naturalistic weirdness that allows scientists to compare how distant different kinds of biochemical architectures are to each other in terms of their (in)compatibility, so that more compatible ones are more close to each other than less compatible ones.

4. Epistemic Weirdness

Is it more difficult to predict what some form of life might look like, the more its biochemical architecture departs from standard life? Davies et al. (Ibid.) argue that we will only be able to successfully detect alternative forms of life if they produce phenomena which we can reliably distinguish from the abiotic environment and artifacts on the basis of our current scientific knowledge of life. Accordingly, what explains predictive difficulties in hypothesizing about non-standard life is not that it possesses non-standard traits. Rather, it is that we possess much less reliable scientific knowledge about non-standard life than we possess about standard life. One of the reasons why silicon has been considered attractive as a potential carbon-alternative is that it can form molecular structures analogous to functional groups from organic chemistry (Petkowski, Bains & Seager 2020). A silicon-based metabolism would of course use a completely different, i.e., inorganic, set of chemical substances as standard life. However, this does not mean that silicon biochemistry and standard biochemistry cannot lead to various evolutionary convergences. This might include highly similar morphological traits on levels of biological hierarchy higher than the cellular level, such as camera-eyes of nervous systems. It also might include inorganic waste products of metabolic activity or other causal impacts on the abiotic environment produced by extant life. In other words, what makes it so difficult to determine how to search for silicon worlds is not that silicon-based biospheres cannot produce phenomena that standard life produces. Rather,the problem is that we can only constrain the possibilities very little on the basis of the evidence available to us. Davies et al. (Ibid.) high-light this point when they write that a "fundamental obstacle in searching for life as we do not know it is that we cannot be sure what to look for."

Some form life A that is biochemically more incompatible with standard life than some other form of life B will share less biochemical traits which we can hypothesize about on the grounds of currently available evidence – textbook knowledge, data from experimental studies, computer-simulations, theoretical investigations, etc. In this sense, it is accurate to consider predictions about silicon worlds more difficult to justify than

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predictions about RNA worlds. It is still unclear whether an RNA world ever existed on Earth. Likewise, it is unclear whether it is possible for silicon-based life to exist. However, there are more aspects of the molecular architecture of RNA-based biospheres that we can reliably hypothesize about than there are aspects of the molecular architecture of silicon-based life. It seems reasonable to expect that non-standard life forms closer to standard life than silicon-based life would be but more distant than RNA-worlds would fall somewhere in between.

Having said that, any such correlation is contingent on the evidence that is actually available to the scientific community at any given time. Consider a hypothetical scenario in which some future astrobiologists had successfully gained access to some biochemically very distant form of life. Imagine, for instance, that these future astrobiologists had been able to detect and exhaustively study a silicon-based biosphere S in the methane lakes of Titan. In that case, scientists may have been able to develop chemical models for the search for silicon-based life on extrasolar worlds. And yet, like astrobiologists today, these researchers would still lack a working model of some non-standard kind of carbon-based life C that does not use nucleic acids and amino acids. If it was more difficult to search for S than C because S is more distant than C from standard life, these hypothetical future astrobiologists should still find it more difficult to search for S than C.

As it does not have to be the case that predictions about alien life are less reliable, the more its biochemical architecture departs from standard life, it makes sense to analyze how unpredictable life is separately from how biochemically different it is. In both instances, we can think of "weirdness" as a form of incompatibility. We can use the term "naturalistic weirdness" to refer to forms of life that are biochemically incompatible with standard life. The more incompatible its biochemical architecture with standard life, the weirder it is, naturalistically speaking. Another sense of incompatibility is epistemic. Roughly speaking, two facts or claims are incompatible with each other, if they cannot both be true at the same time in light of the available evidence. "Epistemic weirdness", in this regard, can be thought of as a measure for how incompatible some hypothetical or actual form of life is with currently established, commonly accepted scientific knowledge.

Again, this suggestion is tentative. Further specification and differentiation will be necessary. What matters for scientific theorizing and practice is to provide a coherent framework for epistemic weirdness that allows scientists to compare how implausible or improbable it would be for life in our universe to have some traits rather than others.

5. Conclusion

In conclusion, it is fruitful to distinguish between ways in which alien life might be incompatible with the standard chemical architecture of extant life and ways in which alien life could be incompatible with commonly established scientific beliefs about life. The former type of incompatibility we can dub "naturalistic weirdness", the latter one "epistemic weirdness".

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