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Convergent evolution and the search for biosignatures within the solar system and beyond

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ABSTRACT

Defining unambiguous biosignatures (isotope ratios of certain chemical elements, organic compounds or other phenomena strongly indicative of past or extant biological activity) is essential for the success of the two existing scientific enterprises, astrobiology and SETI, concerned with the search for extraterrestrial life within our Solar System and beyond. The field of astrobiology is divided into the characterization of likely habitable regimes within the Solar System, such as the subsurface environments of the icy moons Europa and Enceladus, and their future exploration through advanced robotic missions and a more astrophysical approach seeking, first, to identify potentially habitable worlds beyond the perimeter of the sun and, secondly, to detect possibly active biological processes on these planets via spectroscopic analysis of their atmospheres with next generation space-based telescopes. Both research projects within astrobiology are highly interdisciplinary in nature, encompassing the work of biologists, astronomers, planetary scientists and geologists. SETI, on the other hand, was dominated by radio astronomers and engineers since its onset in the early 1960s. At the same time, the research subject of SETI studies was more daring than that of astrobiologists from the very beginning: the detection of extraterrestrial intelligences by means of technology-mediated radio signals. The initial focus of SETI on radio signaling has been broadened to include optical, infrared and targeted exoplanet searches in recent times. Here it is suggested, that the hypothesis of universal convergent evolution might provide a shared theoretical framework for astrobiology and SETI, dealing with the emergence, evolution and future development of life, intelligence and culture. In the most general sense, convergent evolution refers to the independent and repeated emergence of a certain adaptive trait in distantly related lineages. On Earth, convergent processes become apparent on a broad biological spectrum ranging from the molecular sequence level, to morphology and up to intelligent behavior among a number of non-primate species. This paper explores the hypothesis that convergent evolution might not be restricted to Earth and could indeed present a universal mechanism shaping and linking the multiple emergence of life and intelligence across the Cosmos in an analogous manner. Implications for the detection of biosignatures on Europa, putative life on exoplanets and the SETI enterprise are sketched out.

1. Introduction

One of the most debated issues in theoretical biology is the contingency vs. convergence or, in other terms, chance vs. necessity problem. This debate is posing the question about the existence of universal laws governing the emergence of analogous forms of biological complexity across the terrestrial

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and putative alien biospheres. On the one hand, it is possible that the kind of biology we see on Earth and might encounter on other worlds is determined primarily by contingent events occurring in the respective evolutionary history. In contrast to this notion, a small but growing number of researchers is favoring the possible existence of universal laws shaping similar features of independently originating and evolving life forms in comparable planetary environments [1–8]. The orthodox solution to the problem, however, proposes a scenario in which evolution is rather a stochastically-driven process in which its outcomes are contingent on planetary history and chance mutations. Convergent adaptations, independently and repeatedly evolved complex features, are mostly explained due to ancestral inheritance, i.e. *deep homology* [9–12]. Others are suggesting a compromise between these distinct evolutionary forces [13].

Notably, the contingency or chance perspective is essentially a continuation of the "modern evolutionary synthesis", which presented the core of evolutionary biology since the 1940s. Continuing work on the origin of life and proto-cellular evolution is suggesting that this relatively old evolutionary paradigm is not adequate anymore to fully capture the processes that were active during the onset of emerging biological complexity [14–19]. Collective phenomena among cohorts of early cells, *progenotes*, especially the exchange of genetic material via horizontal gene transfer (HGT), are suggested to have determined the emergence or "crystallization" of the first, fully integrated, cells as we know them. These, in turn, were then able to undergo Darwinian, or vertical, evolution. A perspective in which poorly integrated progenotes were engaged in rampant HGT and then evolved towards a Darwinian bottleneck, that could have entailed distinct events of cellularization, is consistent with the notion of convergent evolution [20]. Assuming that similar, if not identical, processes of far off-equilibrium phenomena involving geochemical gradients in aqueous environments [14,21,22], could have led repeatedly to the emergence of life in comparable, ancient planetary habitats, alien organisms should have experienced a phase of extensive HGT and ensuing (multiple) cellularization too. From this point onwards it becomes exceedingly difficult to reasonably predict what kind of adaptations putative life, for example, on the icy moons of Jupiter and Saturn, Europa and Enceladus, or on a far-away exoplanet, would evolve in the course of their history. Nonetheless, exactly this type of predictability is essential to the astrobiological endeavor [23], because future planetary exploration missions or space-telescope based exoplanet surveys need to be guided by a defined, or at least constrained, set of possible biosignatures. Here it will be argued that the notion of convergent evolution is pivotal in lending a certain degree of predictability to astrobiology and the related SETI field.

2. Minimal convergent traits

In order to better understand how the most basic entity, which we could identify as a living organism, should look like, let us turn to the origin of biological evolution again. Life on Earth has evolved in a manner suggestive of a minimum set of prerequisites which comprises liquid water, biogenic elements (C, H, N, O, P, and S) and biologically usable energy (i.e. transducible into chemical bonds for storage and later usage in metabolic reactions). In regard to the most pressing constraint for the onset of a potential biosphere on Europa, for instance, namely available energy sources, recent studies including theoretical work and on-going hydrothermal laboratory experimentation have stressed the importance of evolutionarily conserved molecular "disequilibrium converting engines" in the proto-metabolism of early terrestrial life. This work is part of the "Submarine Hydrothermal Alkaline Spring Theory" for the emergence of life [24–26]. It posits that off-ridge alkaline hydrothermal springs reacted with the metal-rich carbonic Hadean Ocean. During this reaction compounds such as hydrogen, methane and ammonia, as well as calcium and traces of acetate, molybdenum and tungsten were released by progressing serpentinization of ultramafic rock, thereby offering a sustained source of chemically transducible energy for early biological systems [27]. Employing an ancient molecular apparatus resembling the ATP synthase complex, universally observed in extant life, to harvest the free energy contained in the resulting proton and redox gradients, these ancestral organisms could have been able to maintain and gradually increase the complexity of their metabolic and replicator systems [28–31]. Assuming that conditions during the late stages of Europa's planetary differentiation might have been comparable to Earth's Hadean Ocean in terms of a rocky mantle exchanging chemicals and heat with an overlying slightly acidic water layer, many studies point at the importance of putative hydrothermal circulation systems as possible environments conducive to an alternative origin of life [32–34].

In analogy to the triad of parameters that is defining habitability for life as we know it, here a new and simple framework for constraining putative alien biological systems is introduced (Fig. 1). Just as a given world must possess three basic requirements (liquid water, biogenic elements and an energy source) to be rendered habitable, biological entities that we could identify as such, should display three universal Minimal Convergent Traits (MCTs): 1) molecular replication and inheritance, 2) cellularization via membrane systems and 3) metabolic networks coupling energetically favorable biochemical reactions. These MCTs represent systemic properties of an alien organism. It is not implied that extraterrestrial biology necessarily employs an identical set of molecules known from terrestrial life to sustain these features. In any case, if one of these traits is lacking in extraterrestrial organisms, we could not recognize them as life as we know it (and they would not be viable according to our current understanding of biology in the first place). Conveniently, as we shall see below, distinct detection methods are associated with each respective MCT.

Putative microbial life on Europa, Enceladus or Mars would certainly display MCTs and should remain in the unicellular stage due to limiting environmental factors. In the case of Europa, however, the possibility of even higher degrees of biological complexity has been suggested.

3. The possibility of advanced biological complexity on Europa

Next to the water column and seafloor of the deep sea, its underlying sediment presents the largest potential habitat on Earth [35]. On Europa and Enceladus the