# Using exoplanets to test the universality of biology

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# Using exoplanets to test the universality of biology

## The detection of biosignatures on extrasolar planets would allow us to explore the predictability of evolution. What could we learn without directly obtaining a sample of life?

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A profound unanswered scientific question is to what extent biological evolution is deterministic. In other words, how universal are the characteristics of life?[1] (Fig. 1). Exoplanetary science offers us the potential to search for other examples of life in the Universe and to find out whether Earth's evolutionary experiment is an idiosyncratic and contingent outcome, unique to this planet. How far could exoplanets take us in this endeavour?

It is clear that even if we found a gaseous signature associated with life in the atmosphere of an exoplanet, let us say an atmospheric disequilibrium of oxygen and methane[2], we would be denied a great deal of information about that life. Short of the science fiction possibility of an exoplanet sample return mission, which requires a planet within a reasonable distance and a considerable improvement in propulsion technology, we will be unable to get a material sample of the extraterrestrial biology. This is categorically different to the search in our own Solar System, where the discovery of life could be followed by its collection and subsequent laboratory analysis. Although the task of using exoplanets to understand the universality of life may seem insuperable, I suggest there are a surprising number of directions we might take.

Fig. 1 **Universal biology?** Potentially habitable exoplanets will exhibit a diversity of characteristics, including differences in planetary composition and atmospheres. Does this imply a plethora of evolutionary outcomes, or convergence to a similar structure of life? Credit: PHL@UPR Arecibo.

Consider the hypothetical detection of a putative life-bearing planet. What else might we learn other than that it hosts life? We might seek the ancillary signature of water in the atmospheric spectrum and thus be able to say that like life on Earth, this life likely uses water as its solvent. That would constitute a simple observation, but one that is important with respect to the long-enduring discussion on whether life can use an alternative solvent to water, such as liquid ammonia[3].

For example, the detection of an atmospheric biosignature in a spectrum that otherwise suggested a lack of water, but an abundance of an alternative solvent such as ammonia would be a remarkable discovery. Conversely, the detection of many life-bearing planets associated with liquid water would not prove the incompatibility of other solvents with life, but it would strongly suggest either that other solvents are incompatible or that the abundance of water on planetary bodies is such that other evolutionary experiments invariably use it. We would also know that the use of water as a solvent in biochemistry is not a highly contingent and difficult partnership.

The atmospheric biosignature itself would tell us something about the universality of energy acquisition, fundamental to the thermodynamics of how biospheres work. As a waste product of photosynthesis, oxygen would be evidence that life has fathomed how to split water as a source of electrons, suggesting that like life on Earth, this alien biology has rummaged through the periodic table and its associated compounds to find sources of electrons to drive energy harvesting. As it would be strange if a planetary biota had only evolved the capacity to use one source of electrons, we would expect that it would have tapped into others.

Hydrogen, the diverse oxidation states of iron and sulfur, and other simple inorganic electron donors and acceptors are a potentially universal way for life to gather free energy from its environment. By using the inferred density of the exoplanet and observed spectra, we may be able to make predictions on the planet's composition and oxidation state and thus the forms of energy available to life. Expectations on how these modes of energy acquisition would affect the concentrations of atmospheric gases, such as $CH_4$ (produced for example by the methanogenic $H_2/CO_2$ redox couple), $H_2S$ (produced for example by sulfate reduction) or CO (consumed for example in anaerobic carboxydotrophy) could thus be empirically tested. To achieve this we need to advance our observational and modelling capacities to predict planetary compositions and our ability to quantify accurately the concentration of a wide range of gases specifically relevant to energy acquisition.

Exoplanet observation data might allow us to test the universality of the physical boundaries to life. For example, we could attempt to determine the surface temperature of the planet to compare it with the known limits to life on Earth. The upper temperature limit for life is currently set by the microorganism *Methanopyrus kandleri* at 122ºC[4]. There are reasons to suspect that although this temperature could go higher[5], the requirement to repair and synthesise cellular biomass against increasing damage at higher temperatures ultimately establishes a boundary. That organic chemists routinely use ovens to heat glassware to 450ºC to volatilise and remove organic contamination shows that ultimately the stability of the bonds in carbon-based macromolecules sets a limit to life.

If, by convolving the radiation flux of a star with the atmospheric composition of a planet, we were to conclude that a biosignature was associated with a surface temperature of say at least 300ºC across the whole planet, this would be an extraordinary challenge to our knowledge of the putative universal physical boundaries to life. Similarly, low temperature planets and ones with high ionizing and UV radiation fluxes, but with biosignatures, would allow us to test whether these physico-chemical conditions are within the limits of known life. The discovery of biosignatures associated with conditions within the currently known bounds for life would not prove that the extremes for life are universal, but they would strongly suggest that life elsewhere is restricted to similar conditions that bound life on Earth. Testing these limits to biology can motivate us to develop better observational capacities and models to calculate exoplanetary surface and subsurface conditions.

A prominent feature of the Earth's biosphere is the phenomenon of convergent evolution[6], many instances of which can be ascribed to physical limits acting on biology[7]. Although we will not be able to examine individual organisms, we may not be completely bereft of the opportunity to test the phenomenon of convergence on exoplanets. The detection of a biosignature would lead to efforts to study the surface reflectance spectrum to seek, for example, absorbing pigments associated with a biota. The well-known 'red edge' in oxygenic photosynthetic organisms, which is pronounced in land vegetation, is proposed as one such[8]. The extent to which the red edge is a contingent product of terrestrial evolution or a result of functional selection, for example to reject heat in land plants, has been debated[9]. Alternative schemes for energy capture from a star, for example to collect the longer-wavelength infrared radiation from M stars, have been proposed[10].

We would have no way of studying whether the biochemical architecture of the light harvesting apparatus was convergent with terrestrial biology, but we could find out whether the absorbance pigments of surface biota were selected to match the stellar radiation and thus were a feature of biology tightly hemmed in by physical principles. Optimistically, if one had enough of these examples, one could study the correlation between surface pigment absorbances and stellar fluxes to discern convergence, or the lack thereof, of photosynthetic biospheres to their environments.

At a more fundamental biochemical level, exoplanet atmospheric and surface spectra could allow us to test the universality of life's atomic structure. Non-carbon-based biochemistries, for example silicon-based life, remain speculative, but nevertheless a continuing point of discussion[3]. The detection of surface spectra exhibiting complex organic chemistry or the detection of organic carbon-based biosignatures gases, such as methyl chloride, analogous to those produced by terrestrial life[11] might allow us to conclude a carbon-based biology. However, an alternative life might cycle gases such as CO, $CO_2$ and $CH_4$ in energy gathering redox reactions without carbon assimilation into its biomolecules. Thus, the detection of carbon-containing gases out of equilibrium with abiotic processes need not *a priori* suggest a carbon-based life. Nevertheless, a diversity of gases similar to those exuded by terrestrial life as metabolic by-products would suggest a biochemistry similar to ours. Crucial to the success of these studies would be the effective elimination of false positives[12], for example the detection of carbon-containing gases that can be produced abiotically, but yield a false conclusion of a terrestrial-like life.

It is sometimes said that the detection of an exoplanetary biosignature would be a dead-end. With no way to directly sample such a biosphere, all we could do is to find more of these planets in order to derive some statistically satisfying statement about the occurrence of life. Here, I have highlighted just some of the ways in which, from atomic structure through to the physical limits to life, we might use exoplanet observations to test the universality of biology. Testing the hypothesis that the products and trajectories of evolution are universal might lead to the identification of new gaseous and surface spectral features that are not just biosignatures, but can be used to determine characteristics about the underlying biochemistry and structure of life.

If we find no life on any exoplanets and ultimately conclude that we live in a cosmic desert that is devoid of other biology, then we will not have advanced the question of whether the biochemical architecture of life is universal. However, we will have shown that the emergence of the process of biological evolution itself is a contingent event and not a universal convergent outcome of the presence of habitable conditions. This would also constitute a significant insight into the universality of biology.

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