The Power of Self-Skepticism in Astrobiology

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ANY CLAIMS FOR EVIDENCE of life on other worlds have the potential to be transformative events in human history. Accordingly, any such claims will be met with intense scrutiny from the scientific community. This will be particularly true for claims for evidence of life on exoplanets—planets around other stars—for which we will only have remote-sensing data and no ability to grab a piece of that world and put it under both literal and figurative microscopes. The data upon which these claims will be made will be the integrated product of the entire careers of some of the world's greatest scientists and engineers, paid for by considerable taxpayer expense. This presents astrobiologists with a paradox: How can such investments be justified if the end goal is destined to be a highly scrutinized discovery?

The answer to this paradox is presented in a paper in this issue of *Astrobiology* (Meadows, 2017) titled "Reflections on O_2 as a Biosignature in Exoplanetary Atmospheres." The key is to be self-critics in advance and scrutinize our proposed signs of life before we design the instrumentation and missions that would search for those signs. In the terminology of that manuscript, we must consider the "false positives" for biosignatures before we conduct a search for those biosignatures. This leads to a three-step process. First, we must comprehensively consider the potential for nonbiological processes to mimic the signals we believe to be signs of life. Second, we must sufficiently simulate these false positives, as well as biological processes, to identify the secondary measurements that could discriminate between biological and nonbiological origins for the proposed biosignature. Third, we must ensure that these secondary measurements are incorporated into the design of the instruments and missions that will search for the preliminary signs of life.

In the case of exoplanets, the primary signs of life will come in the form of atmospheric gases that are produced by biota at rates that are orders of magnitude greater than nonbiological processes. The example provided by modern Earth is molecular oxygen (O_2), which is the second-most-abundant species in our atmosphere, trailing only nitrogen (N_2). At these high concentrations (21% on modern Earth), O_2 has multiple observable consequences arising from O_2itself, as well as from its photochemical by-products ozone (O_3) and the oxygen dimer (O_2-O_2 or O_4). For decades, astrobiologists and exoplanet scientists have planned missions around detecting O_2 and O_3 features, as it was thought that nonbiological processes could not sustain detectable concentrations of these gases over geological/astronomical timescales.

Recently, a series of theoretical papers has challenged the notion that O_2 and its by-products would only be detectable on inhabited worlds (Domagal-Goldman *et al.*, 2014; Hu *et al*., 2014; Tian *et al.*, 2014; Wordsworth and Pierrehumbert, 2014; Gao *et al*., 2015; Harman *et al*., 2015; Luger and Barnes, 2015). Meadows reviews all this work, which includes approaches from a range of disciplines. For example, photolysis of CO_2 can lead to liberation of O atoms, which can recombine to form O_2 and O_3. This is constrained by geological sources of reducing gases, which act as sinks for these O atoms. But if reducing gases are lost, this would remove this sink and allow O_2 and O_3 to accumulate. Loss of reducing gases could be driven by rapid escape of H from the top of the planetary atmosphere caused by greater fluxes of high-energy radiation from the host star, or by a low-pressure atmosphere not being able to form water clouds that "trap" H atoms in H_2O molecules when they form cloud particles.

By reviewing this work and placing it under a single theoretical framework, this manuscript is an essential read for both the exoplanet and astrobiology communities. For exoplanet scientists, it highlights the commonalities between these false-positive mechanisms and highlights techniques that future missions can utilize to identify them. The corollary to this is that it also allows for the discrimination of "true positives" where the planet is inhabited and producing oxygen on a global scale. The details of the strategies for this will be utilized by future exoplanet observers when analyzing their data, as well as the science and engineering teams that are designing the next generation of telescopes.

For the astrobiology community, the general approach to biosignatures could also be applied to other targets within our solar system. And this approach is consistent with the lessons we have learned elsewhere. Past searches for life on Mars—and for the earliest life on Earth—have demonstrated a need to understand the environmental context of a biosignature (Horowitz *et al*., 1976; Klein *et al*., 1976; Navarro-González *et al*., 2003; Soffen, 1976). In the exoplanet case, the difference is that the signature is global in nature; therefore the environmental context must also be global. The other difference is the forethought given to false negatives. We should strive for such forethought with all biosignature searches across the Solar System, especially those for which follow-up observations will be difficult or impossible.

"Extraordinary claims require extraordinary evidence." That quote has become almost a mantra within astrobiology, which has had a history of contentious claims. The contentiousness is driven by the high-profile nature of astrobiology research, which attempts to address many first-order questions about life and its relationship with its host planet. This contentiousness is also driven by our instincts as scientists to be skeptical of high-profile work, in particular any work claiming to be the first discovery of its kind. What the work by Meadows and the work she reviews demonstrates is the power of advanced skepticism, wherein we critique our own planned evidence before the data are ever collected. This is what allows us to utilize our skepticism proactively and strengthen the case we will eventually make for evidence of life on another world. Given the scrutiny we should anticipate, such an approach is mission critical to any endeavor that intends to search for signs of life on other worlds, regardless of the planetary target of that search.