**Astro2020 Science White Paper**

**A Balancing Act: Biosignature and Anti-Biosignature Studies in the Next Decade and Beyond**

**Thematic Areas:** [x] Planetary Systems

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**Abstract:**

We endorse the findings and recommendations published in the National Academy reports on Exoplanet Science Strategy and Astrobiology Strategy for the Search for Life in the Universe. This white paper extends and complements the material presented therein by elaborating on the need for (and overlaps within) a quantitative biosignature identification and assessment framework that uses prior knowledge and context to produce a numerical estimate for the likelihood that a given world has life. This provides a comprehensive means to weigh planetary habitability alongside potential biosignatures and their respective false positives. Quantitative frameworks for biosignature detection can inform the needed observational capabilities for future exoplanet surveys with a (partial) focus on detecting habitability and life. In general, planetary (and stellar) characterization over broad wavelength ranges will reduce ambiguities and increase our confidence that putative spectroscopic biosignatures are produced by life.

**Motivation**

The last decade has revolutionized our understanding of the frequency of rocky exoplanets, showing that they are common (e.g., Quintana et al., 2014; Coughlin et al., 2016; Kane et al., 2016; Kane et al., 2019), close by (Gillon et al., 2016; Anglada-Escudé et al., 2016; Dittmann et al., 2017), and unique laboratories for understanding the processes that keep the Earth habitable (e.g., Checlair et al., 2018, Kane et al., 2014; Kane et al., 2019). Bounding the limits of habitability underpins what is likely the key motivation for observing these worlds: the search for life. In this vein, the community has outlined biosignatures ranging from atmospheric gases like O2 and CH4, spectroscopic identifications of biotic pigments such as the ‘red edge’, and even the ‘breathing’ of a biosphere in response to seasonal insolation changes (see, e.g., review in Schwieterman et al., 2018). But accompanying this is an evolving list of mechanisms that could mimic these biosignatures, which have been termed false positives, often with their own lists of discriminating features to make them separable from the biosignature. This means that not only must a planet be habitable and present detectable biosignatures, there must also be markers that diminish or rule out the possibility that there is an abiotic agent at work. Conventionally, this has been cast as a decision tree (e.g., the ‘champagne plot’ from Harman & Domagal-Goldman, 2018), but the signs of habitability and inhabitation form at once a pyramid (each factor building on the previous one) and a set of factors balanced against one another.

The balancing act of weighing habitability, biosignatures, and false positives requires specific language at each step, to help quantify uncertainty and the likelihood that a given scenario is most likely driven by life, as well as to identify specific areas for improvement where the clear resolution of statistical likelihood is obscured. A Bayesian approach works well to incorporate critical contextual information, and can include everything from parameters well-constrained by observations of the modern Earth, to factors that are not directly observable (Catling et al., 2018; Walker et al., 2018; see Fig. 1). This makes underlying assumptions about the strength of any given piece of evidence clear and allows for contextual information to add meaningful nuance to the interpretation of observations. Below, we outline terminology and key advances necessary to pursue the goal of detecting life in the face of these issues over the next decade and beyond.



Fig. 1: Conceptual diagram of the Bayesian framework applied to biosignatures. Taken from Walker et al. (2018).

*Habitability markers and precluders*

Habitability markers provide direct or indirect evidence that a surface environment is conducive to supporting life. The most used criterion for exoplanet habitability is the capacity for stable surface liquid water (e.g., Kopparapu et al., 2013; 2016), which bounds the range of insolations that should be targeted for follow-up observations (e.g., Deming et al., 2009; Morley et al., 2017). This criterion can be assessed directly by observing ocean glint (Williams and Gaidos 2008; Robinson et al. 2014) or indirectly by constraining temperature and pressure to be in the stability regime for liquid water. Detection of water vapor (H2O), carbon dioxide (CO2), and nitrogen (N2) would contribute to this assessment. In addition to the narrow and specific requirement that a planetary surface be amenable to hosting liquid water, other surface conditions could be considered such as UV and particle irradiation, which at some intensities may destroy DNA (or other biomolecules), but at some level may be necessary for prebiotic chemistry to occur (Airapetian et al., 2016; Ranjan & Sasselov 2017; Rimmer et al. 2018).

A range of suggestions link the width of the habitable zone to host star type and semi-major axis (Kopparapu et al., 2013), planet mass and radius (Kopparapu et al., 2014), greenhouse gas inventories (e.g., Pierrehumbert and Gaidos, 2011; Abe et al., 2011; Kadoya and Tajika, 2014), and orbital parameters (e.g., Kane and Gelino, 2012), among others. Some of these will be constrained by or inferred from observations, opening the door to a more rigorous statistical approach (Apai et al., 2019). Often missing from these globally-forced estimates, however, is discussion connecting these partially- or super-habitable worlds (e.g., Dressing et al., 2010; Heller and Armstrong, 2014) to potential biospheres. This can range from biosphere size and productivity limitations driven by nutrient availability (Moore et al., 2013; Seager et al., 2013a; Bristow et al., 2017) or photon fluxes (Kiang et al., 2007a,b; Rugheimer et al., 2015; Lingam and Loeb, 2017; Lehmer et al., 2018) to implications for the type and strength of surface biosignatures (e.g., Grenfell et al., 2014). More directly linking gross habitability markers to biological necessities can then link habitability more strongly to biosignature production and detectability.

Contrasting this, direct or indirect evidence that the surface and near-surface environments are inhospitable to known or hypothetical forms of life precludes habitability. For example, UV surface irradiation beyond the limit for dissociating DNA (Rugheimer et al. 2015; O’Malley-James and Kaltenegger 2017), particularly if it is strong enough to dissociate DNA under water to depths beyond photosynthetic active region (PAR) viability (a concern for flaring M dwarfs), would contradict the more general habitability condition provided by liquid water. On the other hand, too little NUV radiation may reduce the availability of precursor molecules relevant to the origin of life (Ranjan & Sasselov, 2017; Ranjan et al., 2017; Rimmer et al., 2018). Other examples could include measured temperatures beyond viability limits for known extremophiles or the absence of water vapor, representing either a frozen or hot, desiccated world.

That said, habitability precluders may not necessarily imply uniformity on a global scale, as evinced by recent work on the nuances of habitability (Yang et al., 2014; Kopparapu et al., 2016; Haqq-Misra et al., 2016). It is then important to constrain what (if any) habitable niches may exist, and what their potential impact could be on atmospheric chemistry, to estimate the likelihood of biosignatures. Because of the overlap of known false positives with conventionally uninhabitable conditions (e.g., Luger and Barnes, 2015; Gao et al., 2015; Airapetian et al. 2017a), it is important to also connect habitability precluders with potential false positive scenarios.

*Biosignatures and anti-biosignatures*

Biosignatures have previously been defined as any “object, substance, and/or pattern whose origin specifically requires a biological agent” (Des Marais and Walter 1999; Des Marais et al. 2008). In the context of exoplanet biosignatures, where only remote information about a planet’s atmosphere and/or surface may be obtained, the classification of a biosignature will be necessarily tentative, thus all remote biosignatures are potential biosignatures. We suggest endorsing the more general definition proposed by Catling et al. (2018): “a biosignature is any substance, group of substances, or phenomenon that provides evidence of life.” In a Bayesian framework, a biosignature is probabilistic evidence in favor of life, such as “an object, substance, and/or pattern that increases the likelihood that the signal is generated by life, such that P(*data*|*life*) is greater than in its absence (e.g., a piece of evidence B is a biosignature if P(*data*|*life*, B) > P (*data*|*life*)” (see Catling et al., 2018; Walker et al., 2018).

Discoveries go both directions; what we learn from Earth’s past and present biosphere and what indelible marks it leaves on the Earth’s atmosphere can continue to inform biosignature searches in the future. Likewise, constraints on the likelihood of conditions conducive to the formation and evolution of life will narrow the focus for future origin-of-life studies. This also means that we work towards a better understanding of the biosignatures for a low- or no-oxygen atmosphere, requiring further exploration of novel biosignatures (Seager et al., 2013b; 2016), as well as more strongly linking habitability drivers to compatible chemical regimes and biosignatures. Biosignature studies have historically relied on 1-D photochemical and climate simulations, whereas clouds and hazes can be spatially and temporally heterogeneous (Fortney et al., 2019) and work to obfuscate any biosignatures. Mapping spectral biosignature retrievals using more complex models could result in more information about the same world (in the same vein as Cowan et al., 2009) and more closely match observations (e.g., Kataria et al., 2015).

An anti-biosignature, on the other hand, is often loosely defined as evidence of chemical free energy in the environment not exploited by life, but this definition is likely inadequate. A broader and more widely applicable definition of an anti-biosignature is given by Catling et al. (2018): “any substance, group of substances, or phenomenon that provides evidence against the presence of life.”  Using a Bayesian framework, Walker et al. (2018) define an “anti-biosignature” as: “an object, substance, and/or pattern that diminishes the likelihood the signal is generated by life, such that P(*data*|*life*) is less than in its absence (e.g., a given piece of contextual information C is an anti-biosignature if P(*data*|*life*, C) < P(*data*|*life*). An equally valid conceptualization would be to define “C” as an anti-biosignature if P(*data*|*no life*, C) > P(*data*|*no life*). CO is particularly relevant as an anti-biosignature because as a reduced form of carbon relative to environmental CO2 it is both a source of electrons and a source of carbon (Ragsdale 2004). In the case of exoplanet atmospheres, the classification of CO as an anti-biosignature is context-dependent: for inhabited, oxygen-rich planets orbiting Sun-like stars its concentration is likely to be very low, but could be substantially higher for planets orbiting M dwarf stars (Schwieterman et al., in press), or reducing atmospheres like the early Earth’s (Kharecha et al., 2005).

*False positive markers and precluders*

 False positive markers provide spectroscopic evidence that abiotic processes are operating that can produce false positive biosignatures. Examples include CO, O2, and CO2 in abundance ratios suggestive of CO2 photolysis or O4 bands that suggest O2 atmospheres too massive to be biologically produced, left behind by a history of robust H-escape (see, e.g., Schwieterman et al. 2016; Meadows 2017; Harman and Domagal-Goldman 2018; Meadows et al. 2018). (In the CO2 photolysis scenario, it is possible CO could be both a false positive marker and an anti-biosignature, though this depends on context.) Crucially, false positive markers are not themselves necessarily anti-biosignatures, since life may exist despite other, non-related abiotic processes generating putative biosignatures. A false positive marker reduces the probability that tentative biosignatures were produced by life, but can only be weighed against the biosignature evidence susceptible to the inferred false positive. In other words, confirming a false positive for photosynthetic O2 does not necessarily rule out non-oxygen biosignatures. Thus, in a Bayesian sense, given a potential biosignature B and a possible false positive marker M, it must be true that P(*data*|*life*, B) > P(*data*|*life*, B, M) ≥ P(*data*|*life*).

 The recent evolution in known false positive mechanisms, especially for planets orbiting M dwarfs, should be a key area for future work. Recent advances have begun to characterize the high energy spectra of stars as a function of age and type (Shkolnik and Barman, 2014; France et al., 2016; Miles and Shkolnik, 2017; Youngblood et al., 2017; France et al., 2018) which will be necessary to bound false positives generated by atmospheric chemistry models. Further work is necessary to quantify variability and flares (Airapetian et al., 2017b; Loyd et al., 2018; Tilley et al., 2019), which potentially overlaps with concerns regarding habitability. From the Earth sciences, a better understanding of Earth’s atmospheric nitrogen and oxygen evolution, driven by feedbacks between biology and geochemical sinks, can inform work related to the formation and preservation of abiotic O2 (e.g., Wordsworth and Pierrehumbert, 2014; Harman et al., 2015). Lastly, improved constraints on critical reactions (e.g., He et al., 2018; Kao et al., 2019) and sink processes (e.g., Harman et al., 2015; Harman et al., 2018) can also limit or rule out some false positive scenarios.

Balanced against this, any spectroscopic evidence that rules out or renders less probable abiotic processes that could produce false positive biosignatures can be said to preclude that false positive. For example, a deficit of non-condensing gases could potentially favor the buildup of abiotic oxygen (Wordsworth and Pierrehumbert 2014; Wordsworth et al. 2017); however, the detection of sufficient non-condensing gases such as N2 through N2-N2 spectroscopic features could preclude this scenario (Schwieterman et al. 2015); alternatively, Rayleigh scattering may constrain atmospheric mass to the extent that this scenario is ruled out (Meadows 2017; Meadows et al. 2018). In a Bayesian framework, given a biosignature B and evidence that makes that biosignature less likely to have been produced by abiotic processes, E, we have: P(*data*|*life*, B, E) > P(*data*|*life*, B) > P(*data*|*life*).

Researchers focused on identifying and quantifying false positive scenarios should be encouraged to go beyond simply reporting the issue, instead striving to include analyses of any potential precluders. Further, such modeling work should happen jointly with observation design such that we can be sure to capture false positive precluders when searching for habitability markers and biosignatures. Identifying additional precluders and/or faster and more reliable methods to retrieve precluder information for currently known false positive scenarios should be a top priority (e.g., Schwieterman et al., 2015).

**Moving Forward**

We reiterate our endorsement of the findings and recommendations published in the National Academy reports on Exoplanet Science Strategy and Astrobiology Strategy for the Search for Life in the Universe. We have provided further context and motivation for a clear and consistent framework to quantify the results of our search for remote biosignatures, which will allow us to go beyond qualitative interpretations to a more robust, quantitative evaluation of how likely we think those signals are to a direct marker for the presence of life. **In general, our confidence that putative biosignatures are in actuality produced by life will increase with more spectral information, making multi-wavelength characterization of potential habitable planets essential**. Additionally, understanding planet-star interactions and consequent atmospheric photochemistry is essential for contextualizing the origin of biologically relevant trace gases and planetary habitability. This argues for support for simultaneous stellar and planet characterization and associated modeling efforts.

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