



Biosignature False Positives

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Abstract

In our search for life – whether within the earliest part of Earth’s geologic record, on planets within our solar system such Mars, or especially for extrasolar

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planets – we must infer the presence of life from its impact on the local or global environment. These “biosignatures,” often identified from the known influence of terrestrial organisms on the Earth’s atmosphere and surface, could be misdiagnosed when we apply them to alien worlds. The so-called false positives may occur when another process or suite of processes masks or mimics a biosignature. Here, we examine several leading biosignatures, then introduce potential false positives for these signals, and finally discuss methods to discriminate between the two using current and future detection technologies. We conclude that it is the astrobiology community’s responsibility to thoroughly exhaust all possibilities before we resort to “life” as an explanation.

Leave No Stone Unturned

The existence of worlds beyond Earth that are capable of supporting life has been the subject of fierce debate throughout history. Within the last 30 years, however, we have moved from philosophy to science. The first observations of an extrasolar planet (or exoplanet) to ultimately be confirmed were made by Campbell et al. (1988), but its presence was not immediately confirmed. The first confirmed exoplanet discovery was a planet orbiting a pulsar (Wolszczan and Frail 1992); the first confirmed exoplanet orbiting a main sequence star was discovered a few years later (Mayor and Queloz 1995). In the last 10 years, NASA’s *Kepler Space Telescope* has added thousands of new data points to a rapidly growing list of exoplanets (Twicken et al. 2016), including Earth-sized planets within the habitable zones of their respective host stars (e.g., Quintana et al. 2014). With the end of *Kepler’s* primary mission in 2013, the subsequent K2 mission and ground-based telescopes have continued making landmark discoveries. These include relatively nearby exoplanets that are potentially amenable to transit spectroscopy observations in the next decade, including the seven-planet system orbiting TRAPPIST-1 (Gillon et al. 2016) and terrestrial planets in the habitable zones of both Proxima Centauri (Anglada-Escudé et al. 2016) and LHS 1140 (Dittmann et al. 2017). But the question still remains: do any of these worlds harbor life? Perhaps more importantly, will we be able to tell?

With the design and construction of increasingly powerful telescopes, we will gain the ability to characterize the atmospheres and eventually the surfaces of an increasing diversity of potentially Earth-like worlds. Such observations will begin with the *James Webb Space Telescope* (JWST), which has the ability to obtain transit and transmission spectra of exoplanets. JWST will be best equipped to obtain such data for larger worlds, but its sensitivities may allow it to detect the largest absorption features on a small number of nearby Earth-like worlds in orbit around cool, low-mass stars (Deming et al. 2009). Greater sensitivities for this kind of observation – likely fine enough for biosignature searches – will be enabled by extremely large ground-based telescopes such as the Giant Magellan Telescope (GMT), the European-Extremely Large Telescope (E-ELT), and the Thirty Meter Telescope (TMT) (Kawahara et al. 2012; Snellen et al. 2013, 2015; Rodler and

López-Morales 2014; Lovis et al. 2017). A second generation of instruments for these telescopes may include coronagraphs that could directly image such worlds and obtain reflected-light spectroscopy which would allow assessment of deeper layers of the exoplanet's atmosphere. However, the ground-based observations will likely be limited to rocky planets in the habitable zones of low-mass stars with intense high-energy radiation (Garcia-Sage et al. 2017).

Observations of rocky planets in the habitable zones of more Sun-like stars will likely require space-based telescopes that are designed from the start with characterization of rocky worlds in mind. Two such mission concepts are currently being studied: the habitable exoplanet observatory (HabEx) (Mennesson and Mawet 2016) and the large ultraviolet/optical/infrared telescope (LUVOIR) (France et al. 2015; Crooke et al. 2016). Both of these missions, as well as the Origins Space Telescope (Cooray et al. 2017), and the *Lynx* X-ray Observatory (Gaskin et al. 2017; Branduardi-Raymont et al. 2017) would conduct transit spectroscopy at complementary wavelengths to the targets ground-based facilities may observe. However, only HabEx and LUVOIR will be able to conduct observations of rocky planets in orbit around Sun-like stars.

As these ideas become reality, we can imagine an ever-expanding cloud of stars and planets with an increasing diversity of properties, all carefully observed and categorized. Information about the atmospheres of these planets could hold the key to finding life on these worlds. But first, we have to understand how to observe the impact life has on its environment, and the ways environments could generate similar observable features.

What We Mean When We Say “Biosignature”

When trying to detect life on planets orbiting other stars, the direct observation of life (e.g., focusing on a single tree in an alien forest, or seeing an alien, or having the alien shake our hand) is incredibly unlikely – They might not even have hands to shake, which would make it impossible, in fact. Within the next several decades, however, it may be possible to observe indirect evidence for that life using the so-called biosignatures. A biosignature is any measurement or observation that *requires* a biological origin to explain what is being measured or observed (Des Marais and Walter 1999; Des Marais et al. 2008; Schwieterman et al. 2017). This would include such indicators as dinosaur fossils, empty candy wrappers, the green haze of a forest too far away to make out the individual trees, or the oxygen we're all breathing. Each of these observations provides indirect evidence, of varying strength, for the presence of extant (or extinct) life.

Biosignatures can be divided into two broad categories: technological (e.g., the candy wrapper) and biological (e.g., oxygen). SETI, in partnership with a number of international groups, has made great strides in monitoring an increasing number of the closest stars to Earth for technological biosignatures (or “technosignatures”) (e.g., Tarter 2001; Welch et al. 2009; Abeysekara et al. 2016). We will focus here on the biological counterpart to life detection (however, we will briefly touch on

technosignatures again when we define “false positive”). Under the broad category of “biosignature,” we can imagine that there are a multitude of observations we can make within our solar system but just a few features that would be observable across interstellar distances. For example, we can imagine (as many of us did when we were younger) going on a hike and stumbling over the fossilized remains of some fantastical beast. We would then carefully examine the fossil and with expert opinions identify what it was like while it was alive. Dinosaur fossils are harder to dig up, however, across the vastness of space. Even with the possibility of traveling to Mars and digging through eons of sedimentary rocks, we are met with the harsh reality that life elsewhere may not share the same complex evolutionary history as life on Earth, preventing us from finding Martian dinosaurs (or other multicellular creatures) that leave clear fossils in the rock record. That said, the elements and conditions that led to life here on Earth are common, and we should expect simple life, at least, to be common throughout the universe (Meadows 2017). The question then becomes: what mark does simple life leave on its global environment that might be seen across interstellar distances?

A Brief List of Biosignatures

We begin by using the Earth as a template in our search for life elsewhere. The abundance of single-celled organisms throughout Earth’s history is recorded in the geologic record and in the atmosphere, and while multicellular organisms have come to dominate the surface today, continents may once have been controlled solely by extensive colonies of microbes (Rye and Holland 2000; Watanabe et al. 2000). The leading contender for the earliest evidence of life stems from the 3.7-Gya (billion-year-old) Isua supracrustal belt in Western Greenland, which features isotopically light graphite, indicating a biological origin (Rosing 1999; Ohtomo et al. 2014). Other possible indicators for life on the early Earth include >3.85-Gya carbon inclusions contained within apatite mineral grains in the Akilia island banded iron formation (Mojzsis et al. 1996) and putative microbial filament fossils captured in the ~3.6-Gya Apex Chert (Schopf et al. 2002) (Fig. 1). Suggested evidence of early life extends beyond Earth, with reports of carbonate globules and pyrite consistent with biology contained in the Allan Hills meteorite ALH84001 (McKay et al. 1996; Thomas-Keptra et al. 2010). These examples highlight our geological search for signs of life, but even if these signals were solidly unambiguous, this approach is untenable (at least with modern technology) for our search for life among the stars. In this case, we must look to ways in which life has made an appreciable impact on the globe.

Biological processes that have globally modified the Earth through time, and that could potentially appear on other worlds, largely produce either (or possibly both) surface or atmospheric signals. The reader is directed to Schwieterman et al. (2017) for an in-depth review of the catalog of potential atmospheric and surface biosignatures, as well as to the chapters “Atmospheric Biosignatures” (Grenfell), “The Detectability of Earth’s Biosignatures Across Time” (Pallé), and “Earth:

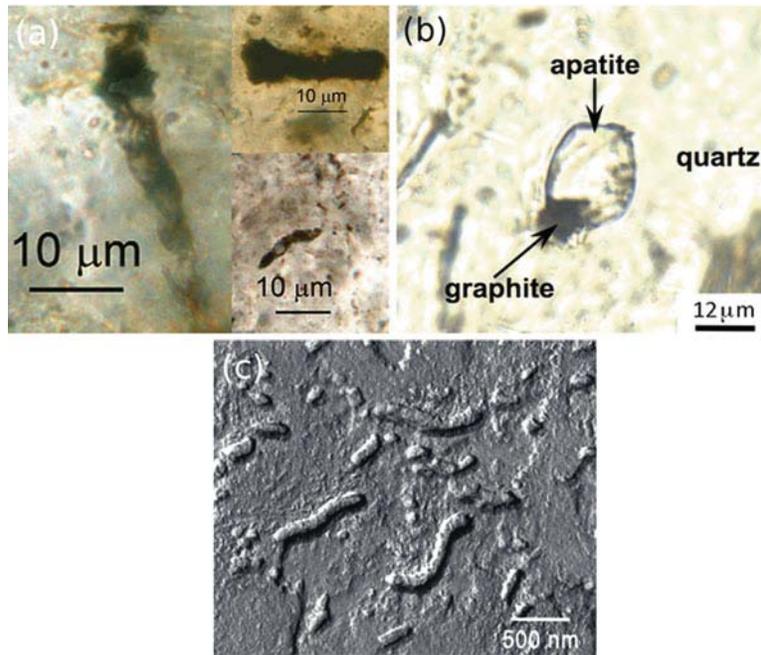
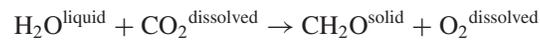


Fig. 1 (a) Optical photomicrographs of Apex Chert inclusions (Image modified from Project 3D 2015 NAI Annual Science Report); (b) images of apatite crystals from a banded iron formation in the Nuvvuagittuq (Isua) supracrustal belt on Akilia island (Image from Papineau 2010); (c) transmission electron microscopy of a cast of ALH84001, purported to show microbial fossils. (Image ARC-1996-AC96-0345-11, JSC/ARC)

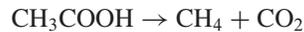
Atmospheric Evolution of a Habitable Planet” (Olson et al.) in this volume. Here, we will highlight just a few.

Molecular oxygen (O_2), which makes up 21% of the modern Earth’s atmosphere, is a direct consequence of oxygenic photosynthesis coupled with organic carbon burial (Kasting and Canfield 2012):

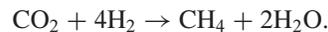


O_2 represents a fantastic biosignature due to its high abundance in the Earth’s atmosphere, its known biological origin, its distinct spectral fingerprints, and its lack of substantial abiotic sources on Earth (Meadows 2017; Meadows et al. 2017). Oxygen-producing life like cyanobacteria (and relative latecomers such as grasses and trees) takes in water (H_2O) and carbon dioxide (CO_2) and then “fixes” the carbon (represented as CH_2O above), making it accessible for other biological processes. The O_2 is then free to accumulate in the water column (where cyanobacteria live) and ultimately exsolve into the atmosphere. While the constraints on when oxygenic photosynthesis evolved are currently obscured by

the sparse geological record, there is strong evidence that it did arise by the mid-Archean (>2.5 Gya) (Farquhar et al. 2011). This is when, due to the prevalence of this metabolism, oxygen concentrations rose to modest concentrations ($\sim 0.02\%$ O_2 by volume, or $\sim 0.1\%$ the present atmospheric level or PAL) (Planavsky et al. 2014). This event is often referred to as the Great Oxidation Event (GOE). Oxygen levels rose again – to near-modern concentrations – in the Neoproterozoic ~ 800 Mya (Kump 2008; Lyons et al. 2014). Following the GOE, O_2 levels were likely high enough to give rise to a thick ozone (O_3) layer which would be potentially detectable with future space telescopes (Segura et al. 2003). Together, O_2 and its proxy O_3 represent arguably the strongest individual biosignature gas, clearly indicating the presence of a substantial oxygen-producing biosphere, as compared to a world without one (Kasting et al. 1984; Kasting 1995; Segura et al. 2003, 2007; Domagal-Goldman et al. 2014). Several extensive reviews of O_2 as a biosignature are available (Meadows 2017; Meadows et al. 2017). Another potential biosignature gas is methane (CH_4) (Des Marais et al. 2002), which is produced under low-oxygen conditions by either the disproportionation of acetic acid (CH_3COOH) into CH_4 and CO_2 (Pilcher 2003; Schwieterman et al. 2017):



or by reducing CO_2 using molecular hydrogen (H_2):



On the modern Earth, atmospheric CH_4 is a trace gas at ~ 1.7 parts per million (ppm) and is largely biological in origin (e.g., Cicerone and Oremland 1988; Kirschke et al. 2013). But earlier in Earth's history, CH_4 concentrations may have been much higher, producing much stronger features in the Earth's spectrum (Sagan et al. 1993; Pavlov et al. 2003; Kharecha et al. 2005; Kaltenecker et al. 2007; Gebauer et al. 2017). It would have been even more detectable on similar planets around different stellar host types (Segura et al. 2003, 2005; Rugheimer et al. 2013, 2015). Additionally, a high $CH_4:CO_2$ ratio (>0.1) may result in an observable photochemical haze (Haqq-Misra et al. 2008; Harman et al. 2013; Arney et al. 2016), consistent with geochemical evidence for the presence of a haze during several epochs in Earth's history (Domagal-Goldman et al. 2008; Zerkle et al. 2012; Izon et al. 2017).

Nitrous oxide (N_2O) is emitted by life when N_2O escapes during denitrification (the reduction of nitrate, NO_3^- , back to atmospheric dinitrogen, N_2 : $NO_3^- \rightarrow NO_2^- \rightarrow NO + N_2O \rightarrow N_2$) (Schwieterman et al. 2017). There are only trace amounts of N_2O in the modern atmosphere, ranging from ~ 270 parts per billion in the preindustrial to ~ 327 ppb today (Warner et al. 2016). Like CH_4 , N_2O concentrations could have been higher earlier in Earth's history (Buick 2007; Roberson et al. 2011) and respond to differences in host star radiation (Segura et al. 2005; Rugheimer et al. 2015).

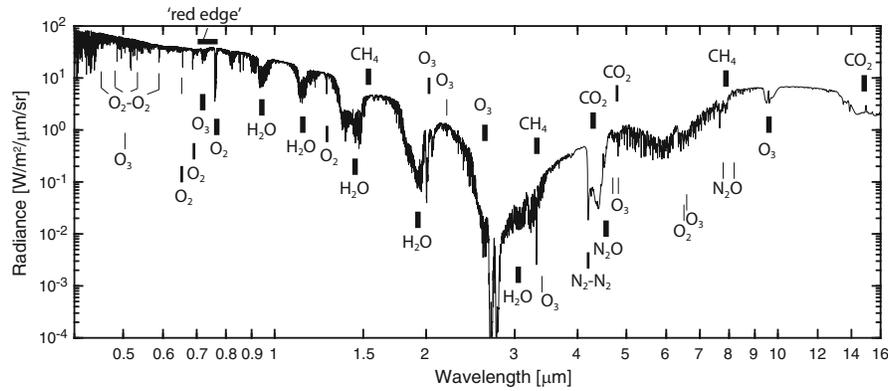


Fig. 2 Simulated spectrum of the Earth matching EPOXI observations for the 24-h average (May 29, 2008) using the 3D Earth model (Robinson et al. 2011). Spectral fingerprints for relevant biosignatures, and their discriminator partners, are highlighted, with the size of the line giving a general indication of the strength of the biosignature relative to its strength at other wavelengths

Besides examining the composition of the atmosphere, we can imagine looking for clues from the presence of life from the wavelength-dependent characterization of a planet’s surface. For example, the “red edge” is a distinctive feature at 0.7 μm , as chlorophyll stops absorbing outside the visible wavelength region (Gates et al. 1965); this can be seen in reflectance spectra of the modern Earth (Sagan et al. 1993) and Earthshine (Seager et al. 2005; Turnbull et al. 2006). Similarly, other biotic pigments (both photosynthetic and nonphotosynthetic) could be detectable, if they accumulate across a significant portion of a planet (Hegde et al. 2015; Schwieterman et al. 2015a, 2017; see also the chapter ▶ “Surface and Temporal Biosignatures” by Schwieterman in this volume).

We can better constrain the life detection problem by considering looking for multiple features, either biosignatures or environmental characteristics, that strengthen our confidence that a biosignature is due to life. For example, CH_4 or N_2O alongside O_2 or O_3 is often cited as the “gold standard” of biosignatures (e.g., Hitchcock and Lovelock 1967; Meadows 2017), as these species would react and exhaust the less abundant gas rapidly without a continuous source (Lippincott et al. 1967; Lovelock and Kaplan 1975; Sagan et al. 1993; Krissansen-Totton et al. 2016). More broadly, a detection of more than one biosignature simultaneously would potentially provide stronger evidence than any one biosignature (Fig. 2).

What We Mean When We Say “False Positive”

In our list of biosignatures, we have included examples from modern and ancient Earth, including speculation as to their behavior on planets orbiting other types of stars. A “false positive” is when a measurement or observation of a potential biosignature could be overlapped (or a discriminating feature obscured) by one or more non-biological phenomena. To say it differently, any abiotic process that superficially resembles a biological process would qualify as a false positive, for example, oxygen derived from photochemical processes instead of oxygenic photosynthesis. As a brief aside, there is also the issue of false negatives, where life may exist, but would be undetectable (Cockell 2014; Reinhard et al. 2017; Olson et al., this volume). Much like the false-positive case, as we discuss below, it could be resolved with additional information.

To return to one of our first examples, let us say we are looking for dinosaur fossils. As non-experts, a false positive could be that we find a strange-looking rock – say, Roccia dell’Elefante (Elephant Rock) on the northern coast of Sardinia, Italy (Fig. 3). Without further information, we would be stymied in our attempts to verify whether or not it was, in fact, a fossilized elephant (or dinosaur, for that matter – we *were* looking for dinosaurs). We could examine it more closely; call in an expert to determine the mineralogy, the local geology, and its history; and come to the conclusion that Elephant Rock is, in fact, a rock. Determining that this was a rock, and not a fossil, involved much more than just identifying the elephant-like shape of the rock. Similarly, early SETI attempts often met with false alarm signals (see Shostak and Oliver (2000) for two brief examples), which has driven innovations in search strategies and technology (e.g., Tarter et al. 2010). This leads to an important point: regardless of the strength of the biosignature, or the presence or absence of documented false positives associated with it, *every* measurement requires contextual information to frame it. And in the cases where false positives could potentially occur, it becomes critical that we (1) work to “inoculate the public against grossly inaccurate information” (Shostak and Oliver 2000) and (2) reinforce all observations with the necessary measurements to discriminate true from false positives. Which brings us back to the biosignatures we have listed above – do any of these have false positives, or fail to remain biosignatures with the addition of new analyses?

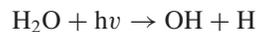
Revisiting Part of the Brief List of Biosignatures

For exoplanets, there are currently a limited number of ways to potentially detect life, but there is a growing list of potential mechanisms capable of generating false positives (Schwieterman et al. 2017). Within the last few years, O₂ has faced increased scrutiny due to its position as the forerunner biosignature, and as a result, several authors have shown that worlds without life, under some circumstances, could accumulate O₂-rich atmospheres. The reader is directed to Meadows (2017)

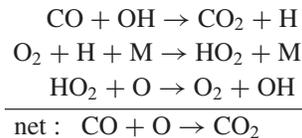


Fig. 3 Left, elephant drinking water (Image by Barbara Piuma from Argentina – Elephant bath, CC BY-SA 2.0, <https://commons.wikimedia.org/w/index.php?curid=5310145>); Right, Roccia dell'Elefante in Castelsardo, Sardinia, Italy (Image by Francesco Canu – Elephant Rock, CC BY-SA 3.0, https://commons.wikimedia.org/wiki/File:Elephant_Rock.JPG). Note the striking resemblance

and Meadows et al. (2017) for a more detailed analysis of false positives associated with O_2 . For example, cold, dry planets with CO_2 -rich atmospheres could build up detectable amounts of O_2 , derived from CO_2 photolysis ($CO_2 + h\nu \rightarrow CO + O$, where $h\nu$ is a photon) followed by the recombination of two O atoms into O_2 (Kasting 1997, 2010; Gao et al. 2015). Additionally, planets orbiting smaller stars experience lower near-ultraviolet (NUV) radiation fluxes than planets orbiting Sun-like stars, which leads to less water vapor photolysis in their atmospheres. Even with temperate surface conditions, a CO_2 -dominated atmosphere can build up appreciable amounts of O_2 and O_3 , again a result of CO_2 photolysis (Tian et al. 2014; Harman et al. 2015). The photochemical source of O_2 in all these cases is dependent on limiting the catalytic recombination of CO and O, the products of CO_2 photolysis, through water vapor photolysis:



followed by



For dry, cold planets, the lack of water vapor inhibits this cycle (Gao et al. 2015); for planets around M dwarf host stars, slower water vapor photolysis achieves the same effect (Harman et al. 2015). In both cases, the accumulation of O_2 to detectable concentrations is governed predominantly by photochemistry and climate.

Two other scenarios can lead to the buildup of O₂, via loss of atomic hydrogen (H) to space. This causes an irreversible oxidation of the atmosphere. One way to achieve this is through a runaway greenhouse, where a planet sufficiently close to its host star heats up enough to evaporate the surface ocean (Kasting et al. 1993; Schindler and Kasting 2000; Kopparapu et al. 2013). Water vapor is photolyzed (H₂O + hν → OH + H), and the light H is lost to space. Conventionally, the habitable zone is defined on the inner edge by the runaway greenhouse (Kopparapu et al. 2013), but the smallest stars (very late M dwarfs specifically) have very long superluminous phases before they evolve onto the main sequence. This means planets within the main sequence habitable zone for these stars were located interior to the runaway greenhouse for the pre-main sequence phase (Luger and Barnes 2015). This pre-main sequence time is short for Sun-like stars (on the order of a few tens of millions of years or less) but can be up to a billion years for the smallest stars (Baraffe et al. 1998). This is sufficient to potentially drive the loss of several Earth oceans of water – leaving hundreds to thousands of bars of O₂ behind (Luger and Barnes 2015). The other water loss process is much gentler and affects those planets that lack sufficient N₂ or O₂ in their atmospheres (Wordsworth and Pierrehumbert 2014). These planets would have temperate climates, but without cold traps for water, allowing high water vapor content in the upper atmosphere and gradual loss of H to space through water vapor photolysis. Atmospheric loss would shut off once ~0.02–0.2 bars of O₂ had accumulated – very close to the amount of O₂ in the modern Earth’s atmosphere (Wordsworth and Pierrehumbert 2014). All of these processes could drive the accumulation of appreciable, and potentially detectable, atmospheric concentrations of O₂.

N₂O is another strong biosignature gas, with few known abiotic mechanisms for formation. There is a tiny abiotic production route for N₂O through lightning in the modern Earth’s atmosphere (e.g., N₂ + O₂ → 2NO) (Schumann and Huntrieser 2007), as well as limited N₂O production in hypersaline ponds (Samarkin et al. 2010). But the ultraviolet (UV) environment for planets around M dwarfs lowers the fluxes necessary to enhance the abundances of biogenic N₂O (Segura et al. 2005), and the same works for N₂O from lightning (Navarro et al. 2014). It has also been suggested that the XUV flux around active M dwarfs can also split the N₂ triple-bond efficiently, leading to N₂O accumulation (Airapetian et al. 2016). However, the reported abiotic N₂O concentrations were still too low (varying from 0.02 ppm at the surface to 3 ppm in the upper atmosphere) and so are likely undetectable (Navarro et al. 2014). Note that while this means the tested scenario fails to generate a false positive, there could be secondary effects not considered that may exacerbate the buildup of N₂O.

The false-positive mechanism for CH₄ is much more straightforward than those for O₂ and N₂O. While life produces the overwhelming majority (>99%) of CH₄ in the Earth’s atmosphere (Kasting 2005), some geologic processes emit small amounts of CH₄ (e.g., Etiope and Sherwood Lollar 2013). Additionally, serpentinization, the hydration of ultramafic (e.g., basaltic) seafloor, releases substantial amounts of H₂, which can (in the presence of CO₂) result in CH₄ production (Guzmán-Marmolejo et al. 2013; Etiope and Sherwood Lollar 2013). However,

there is wide disagreement on the fraction of CH₄ from serpentinizing systems on Earth that is biological, rather than geochemical in nature; this is an important area of future work for this false-positive source. As an edge case, Titan, the largest moon of Saturn, has an atmosphere with ~1.5% CH₄ derived entirely from abiotic sources. Titan also features a substantial haze layer, albeit derived from an N₂-CH₄ atmosphere, rather than the CO₂-CH₄ atmosphere we might expect for the early Earth, which may result in discernable differences in haze optical properties (Arney et al. 2016).

Surface biosignatures offer stronger evidence for life than atmospheric biosignatures, as there are currently no known false positives that precisely match the spectral characteristics of biological pigments. If we also consider surface reflectivity features, such as the vegetation “red edge,” there exist a number of minerals that show a distinctive reflectivity transition similar to the “red edge,” albeit at different wavelengths (Schwieterman et al. 2017). This suggests that, while they may be difficult to detect, pigments of surface communities may be the strongest biosignature (Schwieterman et al. 2017; Schwieterman this volume).

Lastly, the combined detection of several biosignatures, for example, O₂ + CH₄, could have an unusual, although unlikely, false positive. Observations of an unresolved binary planet system, with both bodies having abiotically generated atmospheres, but one oxidized (hosting the O₂ signal) and one reduced (hosting the CH₄ signal), could result in the simultaneous detection of O₂ + CH₄ (Rein et al. 2014). This is an unlikely scenario, but it is still useful as a theoretical worst-case false positive. In order to rule out this false positive for life, the binary nature of the system would need to be confirmed, and the spectra from the two bodies disentangled (e.g. Agol et al. 2015; Li et al. 2016). Once this is done, the same treatment of potential false positives we apply to single-planet systems would be applied to each individual target.

Seeing the Forest for the Not-Trees

The identification of false positives for potential biosignatures is an important step in the search for life, as it allows us to look for associated environmental characteristics that would help us distinguish true from false positives. For potential biosignatures in the geologic record of the early Earth, a similar process has been used, and the analogy for Elephant Rock is apt; often, the identification of life is based on morphology, with later work adding chemical and isotopic data to better constrain biogenicity (i.e., its biological origin). Schopf et al. (2002) reported observing microbial filaments in the Apex Chert, identifying them visually, and verifying the presence of graphite, which is purportedly from altered kerogen (insoluble complex organic matter). However, later reanalysis showed this interpretation did not match the lithology, with the “fossil”-bearing section representing a breccia vein showing signs of repeated hydrothermal alterations (Brasier et al. 2002). This argument is still ongoing in the literature (Schopf and Kudryavtsev 2012; Brasier et al. 2015). Also within the Isua supracrustal belt, the Akilia island apatites were found to house

isotopically light graphite (Mojzsis et al. 1996). However, follow-up work found no graphite associated with apatite crystals, even within the same initially reported sample (Lepland et al. 2005). Much like the biogenicity of the features within the Apex Chert, the origins of the carbon within the Akilia rocks are still debated (Papineau et al. 2010). Stepping away from fossil evidence for life on Earth, the famous Martian “microfossils” featured within the Allan Hills meteorite ALH84001 (McKay et al. 1996) could be the result of inorganic precipitation of carbonates at high temperature, which explains both the morphology and the anomalous ^{13}C enrichment (Golden et al. 2001, 2004).

Moving from the realm of confirmed false positives for geochemical and morphological biosignatures on Earth, we can imagine observing environmental and stellar characteristics when considering biosignatures on exoplanets. For at least two of the false positives associated with O_2 , a determination of the amount of CO_2 in the planetary atmosphere is an important first step (Domagal-Goldman et al. 2014). CO_2 photolysis rates sufficient to produce detectable amounts of O_2 produce stoichiometric amounts of CO , which could be potentially detectable (Schwieterman et al. 2016; Wang et al. 2016). Determining the stellar near-UV-to-far-UV ratio would help constrain the provenance of the O_2 , in this case (Harman et al. 2015). In fact, the stellar near-UV-to-far-UV ratio may be obtained well in advance of the spectroscopic characterization of the exoplanet itself (e.g., France et al. 2013) or by the mission observing the exoplanet (France et al. 2017). Direct surface temperature retrievals would be more difficult (Des Marais et al. 2002) but not impossible (e.g., Maiolino et al. 2013; Brandl et al. 2014) and would provide valuable insight if available, in the absence of constraints on greenhouse gas concentrations (Forget and Leconte 2014). If not, then this would leave a degeneracy in determining the driving mechanism (whether the O_2 is a result of a cold, dry planet, or one hosted by an M star). Constraints on atmospheric water vapor abundance are desirable to rule out O_2 production in desiccated atmospheres (Gao et al. 2015), and water has several strong absorption features throughout the visible and near-infrared. This may also help identify planets orbiting host stars with long pre-main sequence lifetimes that have undergone significant water loss (Luger and Barnes 2015). For these planets, a natural consequence of large concentrations of O_2 is the increasing presence of O_2 collisionally induced absorption ($\text{O}_2\text{-O}_2$, or O_4), which is very sensitive to the partial pressure of O_2 (Schwieterman et al. 2016). For the gentler water loss mechanism outlined by Wordsworth and Pierrehumbert (2014), measuring the amount of N_2 directly is very difficult, but much like O_2 there exists a spectrally active dimer ($\text{N}_2\text{-N}_2$ or N_4) which may be accessible near $4.2\ \mu\text{m}$, although this measurement is likely also challenging (Schwieterman et al. 2015b). Alternatively, this false positive could be ruled out by determining the presence of water vapor clouds in the planet’s broadband continuum, or by looking for narrower atmospheric absorption for all features, due to the lower total atmospheric pressure expected for this mechanism.

For N_2O , given the paucity of potential false positives reported in the literature, we can imagine constraining the UV properties of the star, including extreme UV

(XUV), near-UV, and far UV fluxes from the host star (Navarro et al. 2014). This would allow us to rule out whether a small abiotic source could supply enough N_2O to overcome its photochemical sinks. On the other hand, the observation of CH_4 by itself should not be considered a biosignature, even with an abundance of contextual information, in the absence of additional biosignatures like O_2 . For better or worse, the strongest single biosignature remains O_2 , even in the face of a larger catalog of potential false-positive mechanisms. However, the observation of multiple biosignatures can exclude a number of false-positive scenarios, as well as strengthen the case for life being present. Because O_2 is currently the best potential biosignature for life on exoplanets, if we were to detect it in the atmosphere of an exoplanet, the amount of effort required to constrain the UV environment, as well as the abundances of H_2O , CO_2 , N_2 , and O_2 , and the planet's cloud-coverage and total pressure, would be justified.

Where the Rubber Meets the Road

All these theories are a necessary step to apply our current understanding of biosignatures to the first opportunities we have to explore other worlds within and without our solar system. Future missions to Mars include the prospect of sample return (NRC 1997) and eventually, a human presence on the Red Planet (Levine and Schild 2010). This makes a firm understanding of biosignatures and contextual information from our own fossil record critical, especially when it comes to selection of the small number of samples we will return to Earth. For exoplanets, future large space- and ground-based observatories will offer us an unprecedented look at habitable and potentially inhabited worlds (e.g., Apai et al. 2017; Lovis et al. 2017; Morley et al. 2017; Snellen et al. 2017), potentially within the next 15 years (Fujii et al. 2017). How will these missions make the necessary measurements to validate biosignature detections?

For the detection of O_2 as a biosignature and its discrimination from false-positive cases, we will need (1) stellar UV measurements from at least Lyman-alpha (~ 121.6 nm; the strongest emission line for stars in the UV, driven by the first electronic transition of hydrogen) through to the visible (~ 400 nm) and (2) observations of CH_4 , CO_2 , H_2O , CO , $\text{O}_2\text{-O}_2$, and, if possible, $\text{N}_2\text{-N}_2$. The first, as previously mentioned, is underway for some planet-hosting systems already (France et al. 2013, 2016; Shkolnik and Barman 2014, and subsequent MUSCLES papers) or proposed (Shkolnik 2016). The second point, to observe planetary atmospheric composition, requires observations in the UV, visible, and infrared wavelengths. The strongest of these bands are at 7 to 8 μm for CH_4 , 9.6 μm for O_3 , and the 15 μm for CO_2 band (Schwieterman et al. 2017; Fujii et al. 2017). However, high spectral resolution or direct imaging measurements with large space-based telescopes could detect these gases at near-infrared wavelengths, due to absorption features for CH_4 at 1.8 and 2.4 μm , for CO_2 (at high CO_2 concentrations) at 1.1 μm , and for CO at 2.45 μm .

JWST could potentially perform transmission spectroscopy all the way through the infrared, constraining most of these gases, with tens of transits for some of the nearest exoplanet systems (Morley et al. 2017). However, compared with ground-based telescope capabilities, JWST has only modest spectral resolution, which may push observations of less abundant biosignature and discriminator gases into the 2020s (Fujii et al. 2017). Ground-based telescopes like the VLT, using an adaptive optics system, in conjunction with a high-resolution spectrograph, would require up to 60 transits spread over 3 years but could look for O₂, H₂O, and CH₄ in Proxima Centauri b's atmosphere (Lovis et al. 2017). The extremely large telescopes (ELTs) coming online in the 2020s will be able to retrieve, at much higher spectral resolution, transmission spectroscopy of CO₂, O₂, and H₂O in tens of transits as well, with the caveat that the limited field of view could be problematic (Fujii et al. 2017).

This next generation of ground-based telescopes could also detect and potentially characterize habitable planets via direct imaging using adaptive optics (Apai et al. 2017). And the next generation of flagship space-based telescopes is being designed from the start with a biosignature search, and elimination of false positives for those biosignatures, in mind. These missions – HabEx (Mennesson and Mawet 2016) and LUVOIR (France et al. 2015; Croke et al. 2016) – will have both the UV capability required for host star characterization and starlight suppression to allow for direct imaging spectroscopy of potentially habitable planets. This will provide reflected-light spectroscopy from $\sim 0.3 \mu\text{m}$ to ~ 1.8 (for HabEx) or $\sim 2.5 \mu\text{m}$ (for LUVOIR), including most of the false-positive discriminators. They should be able to detect H₂O, O₂, and O₃ on Earth-like worlds and sufficiently constrain the concentrations of CH₄, CO, and CO₂ in order to eliminate known abiotic production mechanisms for O₂ and O₃.

Taken together, these observational techniques offer the unparalleled opportunity to find, characterize, and say with some certainty whether or not those worlds may host life. One potential approach is illustrated as a flow chart below (Fig. 4), allowing observers to selectively pursue further observations of those terrestrial planets with promising conditions or biosignatures. Right now, we have a limited catalog of Earth-sized exoplanets within their host stars' habitable zones, but future missions such as the Transiting Exoplanet Survey Satellite (TESS) and the CHaracterising ExOPlanet Satellite (CHEOPS) (Broeg et al. 2013; Ricker et al. 2014; Fujii et al. 2017), which are scheduled to launch in 2018, will add more. Continued advances in transit surveys and radial velocity instrumentation for ground-based telescopes will further add to the diversity of known planets with the potential for global biospheres (Meadows 2005). This suggests that, relatively soon, we may be able to pick only the most promising targets (i.e., those with the fewest potential for false positives) for more detailed follow-up studies. Although not as high a priority, we can also observe targets with higher potential for false-positive generation, as a test of the atmospheric and planetary science theories that predict their existence.

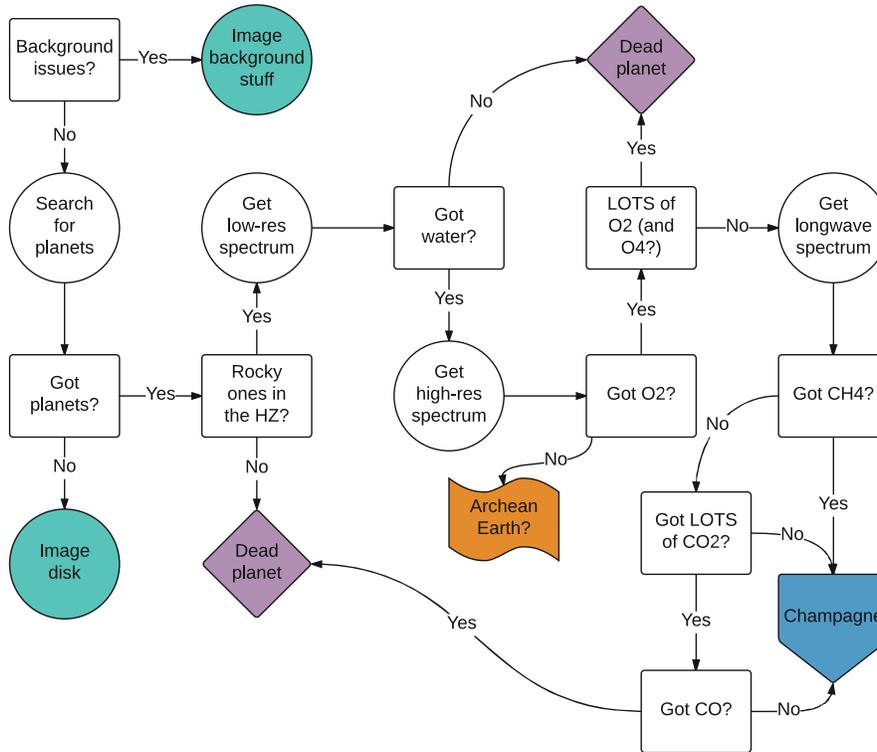


Fig. 4 Starting from the top left, this flow chart shows a plausible series of observations used to determine whether an extrasolar planet may harbor life. In this example, we are searching for surface photosynthetic life, as we have here on Earth, which takes in water and carbon dioxide (CO_2) and exhales molecular oxygen (O_2). Several measurements along the flow chart discriminate selected false-positive scenarios from the literature, as described in the text

Conclusions

With *Kepler*, we got our first glimpse behind the curtain, allowing us to begin to firmly ground our expectations for the prevalence of Earth-sized planets in the galaxy. Within the next few decades, our community will begin to unravel whether or not worlds other than our own may have life. Along the way, we are sure to face surprises – and potentially sensational false positives. In preparation for these observations, and our discovery announcements to the public, we should use our theoretical and practical understanding of planetary processes to predict as many “false positives” for life as possible. This will leverage lessons we have learned from the search for life in Earth’s ancient rock record (c.f., Buick 1984) and prior claims of life on Mars (Levin and Straat 1977; McKay et al. 1996) that are not generally accepted by the science community. To paraphrase David Hume, a wise scientist weighs their convictions against the evidence or, as Carl

Sagan popularized it, “extraordinary claims require extraordinary evidence.” As such, the astrobiology community needs studies that tie the solid planet, potential biology, atmospheric chemistry and dynamics, and the host star together. This systems science approach will afford us the necessary expertise to diagnose false positives and validate any signs of life we may find elsewhere in the universe. Any biosignature without sufficient context is untrustworthy, and it is our responsibility to exhaust the alternatives (and heavily caveat the statement) before declaring that we have found life.

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