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Signs of life on a global scale: Earth as a laboratory for exoplanet biosignatures

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Thousands of planets orbiting stars other than the Sun (exoplanets) have been discovered, and the pace of discoveries will only accelerate as new observing missions are deployed. As the state of the field moves from exoplanet detection to characterization we are inching ever closer to in-depth determination of the properties of rocky planets within the so-called ‘habitable zones’ of their host stars. The question now becomes—how would we recognize the signs of habitability and life on a distant exoplanet? We must begin with the only known example of a habitable and inhabited world—our own. But Earth affords more than one glimpse into conditions on a life-bearing world. Throughout geologic time the prevailing atmospheric and chemical state of our planet has undergone titanic shifts including from a hazy, orange, oxygen-free, methane-choked global habitat to the oxygen-rich pale blue dot we now take for granted. Here, we discuss ongoing efforts by astrobiologists and astronomers to catalogue the potential signatures of habitability and life we may find elsewhere in the universe by using Earth—both present and past—as a laboratory for the possible signatures of inhabited exoplanets.

Viewing the pale blue dot from afar

Images from space reveal our planet as a dynamic place resplendent with oceans, continents and clouds. These global views illuminate a planet not only with abundant surface liquid water (one commonly accepted definition of ‘habitable’) but in places covered with the characteristic green hue of vegetation and therefore life (Figure 1a). However, views of Earth-like exoplanets will be far less striking than images of our own planet from close orbit.

Instead of a 2D representation of the planet complete with spatial information, the best we can hope for over the next few decades is a spatially condensed version of the planet with all relevant information collapsed down to a single point of light. A representative but closer-to-home example is the image Voyager 1 took of our home planet from approximately 6 billion kilometres away (Figure 1b). The well-known astronomer and noted science communicator Carl Sagan poetically described the Earth in this image as a “mote of dust suspended in a sunbeam”.

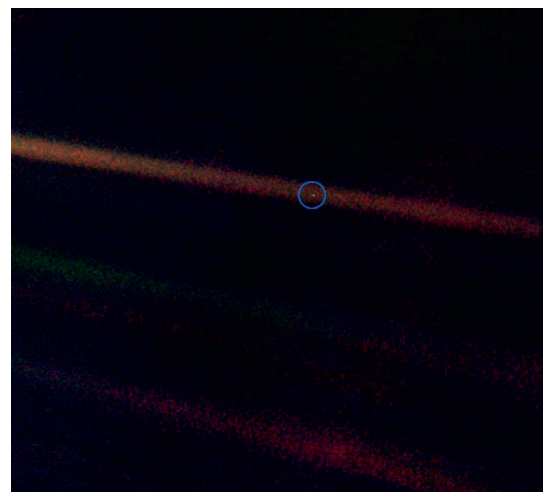


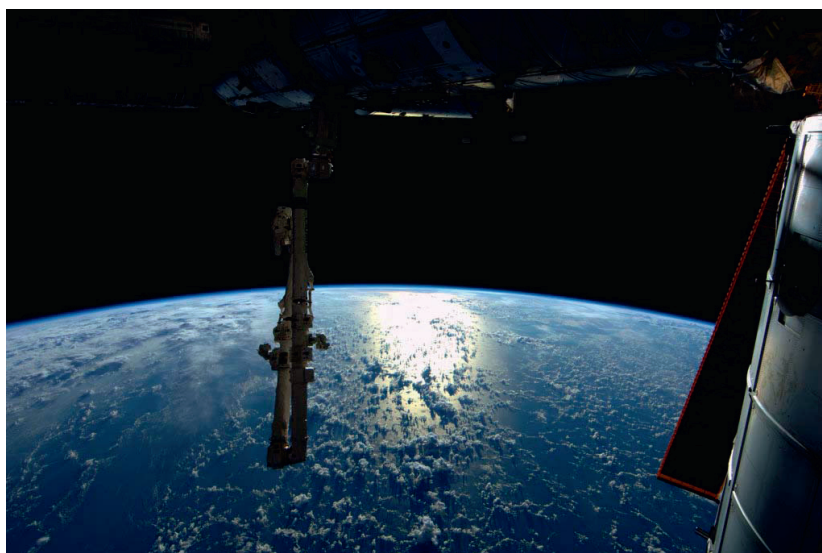
Figure 1. Left panel: image of Earth from the DSCVR spacecraft (image credit: NASA). **Right panel:** an image of Earth captured by Voyager 1 from approximately 6 billion kilometres away (image credit: NASA / JPL-Caltech).

Teasing out the signs of habitability and life from this mote, also famously referred to by Sagan as a “pale blue dot”, is a challenging proposition. Indeed, it is even more so the case for exoplanets than for Voyager 1, since the nearest exoplanet known is not mere billions of kilometres away but over 40 trillion kilometres from us. There are, however, reasons to be optimistic. Both the intensity of light and its colour offer clues into the atmospheric and surface composition of the target world. By breaking up the light into its component colours we can learn about the atmospheric fingerprints of the planet and, in principle, link these to the geological and biological processes that generate them. Indeed, advanced computational models that can simulate the spectral appearance of planets are being validated by remote observations of solar system worlds (including Earth, Mars and Venus) by interplanetary spacecraft. We can also use Earthshine, light from the Earth reflected by the Moon and collected by Earth-bound astronomers, to learn about the remotely detectable signatures of a habitable planet.

Remote signatures of habitability and life

The search for life begins with the pursuit of habitable environments, and to planetary scientists habitability means one thing above all others: liquid water. The oft-promoted ‘habitable zone’ refers to the range of distances around a star where liquid water can exist on a planet with certain atmospheric properties—any closer to the star and water will boil away, too far and it will all freeze. Being in this zone is a good start but does not necessarily guarantee habitability. So, if a planet is in its ‘habitable zone,’ i.e. the planet is at the right distance from its star given the intensity of that star’s light—how would we confirm it is really habitable? One way would be to directly detect the presence of liquid on the surface. This could be done by looking for the characteristic ‘glint’ of an ocean (Figure 2). This glint signature would change in intensity as the planet changes position along its orbit and so could be identified even in the absence of any spatial information. Three-dimensional spectral models of Earth, validated by real observations of the pale blue dot, have demonstrated the feasibility of this type of observation. Additionally, the atmospheric signatures of liquid water and carbon dioxide would support both the presence of water and the greenhouse warming necessary to keep the planet’s surface hospitable for life.

Of course, just because a planet is habitable does not necessarily mean it has developed life. Locating a planet that could be habitable is just one step; the next is to find affirmative indications for life—often termed ‘biosignatures.’ A biosignature is defined as a substance, object or pattern that is both produced by life and can be



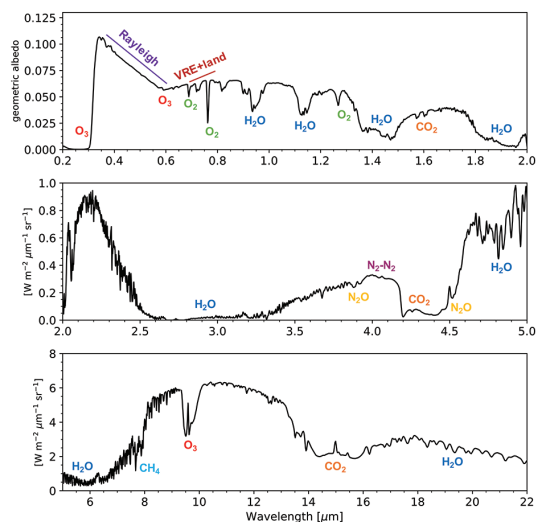
separated from potential abiotic (non-living) processes. In the summer of 2016, a team of astrobiologists under the auspices of the NASA-coordinated network Nexus for Exoplanet System Science (NExSS) met to develop a summary of the past, present and future of exoplanet biosignature research. This effort culminated in the recent publication of a special issue on exoplanet biosignatures in the peer-reviewed journal *Astrobiology*. Among the topics pursued was the assembly of various methods for grouping potential biosignatures. One way to do this is to consider how these signatures would manifest themselves to an observer. In this scheme, biosignatures can be grouped into gaseous (or atmospheric) signatures, surface signatures and temporal (time-dependent) signals.

The most commonly cited **gaseous biosignature** is molecular oxygen (O_2) because plants, algae and cyanobacteria are the dominant source on Earth and because the oxygen in our atmosphere would be quickly consumed by geologic sources without constant replenishment by life. However, biology need not always be the primary source of oxygen for planets orbiting other stars, leading to potential ‘false positives’ for life. Such false positive scenarios, and methods for distinguishing them from ‘true positive’ biosignatures, remain a major area of important research.

Other examples of biosignature gases can include ozone (O_3), a photochemical product of oxygen, methane (CH_4), produced by organisms called methanogens and nitrous oxide (N_2O), often generated by denitrifying bacteria. A combination of multiple biosignature gases would be stronger evidence of life than any one alone; particularly if they were in chemical disequilibrium—in other words, if they would ordinarily react quickly and destroy each other. Their simultaneous presence suggests

Figure 2. Image taken by ESA astronaut André Kuipers of the ocean glint seen from the International Space Station (Credit: NASA / ESA).

Figure 3. Simulated spectrum of Earth generated by the Virtual Planetary Laboratory's 3D spectral Earth model (credit: doi.org/10.1089/ast.2017.1729)



that they are maintained by a constant source at high rates that could require life. Unsurprisingly, Earth's spectrum displays the fingerprints of oxygen, ozone, methane and nitrous oxide in chemical disequilibrium, suggesting evidence of life, in addition to water vapour and carbon dioxide, which provide evidence of habitability (Figure 3). The presence of nitrogen gas (N_2)—which is abundant but difficult to detect—would further support the interpretation that the Earth is both habitable and hosts life.

In practice, observing some of these signatures on a distant exoplanet will be difficult, as only portions of the electromagnetic spectrum will be accessible for a given telescope, and separating these from the high

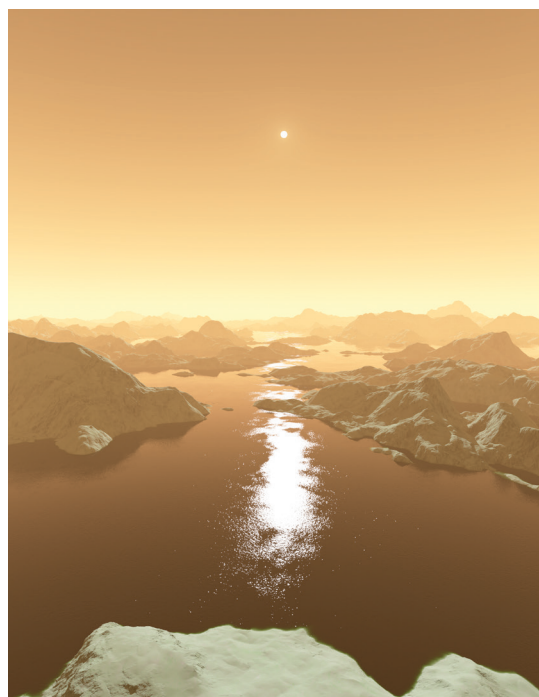


Figure 4. Artist conception of a view on the surface of Archean Earth (Image credit: Dr Giada Arney)

background electromagnetic output of the planet's star will be challenging. To be truly convincing, atmospheric biosignatures must have three essential properties: they must be provably produced by life, they must be detectable remotely, and they must accumulate in the atmosphere and survive photochemical reactions that can destroy them. This last part can preclude some potential biosignature gases. For example, isoprene is a compound widely produced by life but is quickly destroyed in the atmosphere before it can reach concentrations that would be detectable over interstellar distances. (Intriguingly, this survivability threshold will be different depending on the spectrum of an exoplanet's host star and the consequent photochemical reactions it drives, thus the suite of possible biosignatures may change from star to star.)

Surface biosignatures are markers found in the absorption and reflection properties of a planetary surface that are attributable to life. The most notable example on Earth is the vegetation red-edge effect (or VRE) in plants due to absorption of most visible light by chlorophylls and other pigments in combination with the strong reflection of infrared wavelengths. This 'red-edge' is commonly used by Earth observers to map vegetation and plant health and can sometimes be seen in the spectrum of Earth's light reflected by the Moon.

Temporal biosignatures are time-dependent modulations of gaseous or surface biosignatures that are tied to life, such as those produced by seasonal variation in rates of photosynthesis. For example, the carbon dioxide concentration of the Northern Hemisphere increases as vegetation grows in the spring and summer and decreases as it withers and decays in the autumn and winter. In essence, this is a signature of our biosphere 'breathing.' However, we do not necessarily expect the signs of life on an exoplanet to be an exact replica of what we find on Earth today. Instead, the closest example of far different alien planets may be found by searching deep within our own geologic record.

Alternative Earths: how our planet's past illuminates the search for life beyond

Over 3 billion years ago, during a geologic eon known as the Archean, our planet would have been almost unrecognizable. If you were standing on this ancient Earth, there would be no oxygen to fill your lungs or blue sky to meet your gaze. Instead, the atmosphere was replete with methane, and (for at least intermittent periods) this hefty supply of the gas would have given rise to a hydrocarbon smog, or 'haze.' This haze would have cast a dull orange pall across the landscape (Figure 4) like that seen today on Titan, a moon of Saturn. Indeed, this hydrocarbon

haze has been suggested as a potential biosignature itself, since on a terrestrial planet with abundant carbon dioxide (unlike Titan), it requires a large source of methane that may necessitate the presence of methanogenic microbes (archaea). Work is ongoing toward more quantitative constraints on the possible sources of methane that do not require life, such as through a geologic process called serpentinization (so named for the characteristic patterns in rocks undergoing this process, which are evocative of lizard-like skin). The types of biosignatures present on an Archean world may not be limited to methane but could include organosulfur gases (particularly on planets orbiting stars where photochemical build-up is more favourable) and ‘near-infrared-edges.’ The latter is analogous to the modern vegetation red-edge but is instead produced by mats of photosynthetic bacteria that do not produce oxygen.

Between 2.3 and 2.4 billion years ago, our planet’s atmosphere began to change dramatically, marked most importantly by the first appearance of free oxygen (Figure 5). This marked the start of the geologic eon known as the Proterozoic. We know the chemical state of this bygone world partly from the geologic record, which provides us with diverse types of evidence for the first appearance of atmospheric oxygen around this time. However, the magnitude of change in oxygen abundance required to explain the data is very slight, and recent geochemical evidence suggests this increased level may still have been less than 0.1% of the present atmospheric level (that is 0.1% of 21% or less than 0.02% by volume!). It was not until the last several hundred million years, at the end of the Proterozoic eon and the beginning of what is now the Phanerozoic, that the oxygen content of the atmosphere rose to levels comparable to those observed today with tremendous consequences for the evolution and diversification of complex life, such as animals, and the remote detectability of our biosphere.

The remote biosignatures of Earth during these three eons would have varied immensely. Methane and perhaps organic haze would have been prominent in the Archean, while oxygen and ozone are most prominent in the current Phanerozoic eon. This possibility already poses a challenge because of the suggestion that clear signs of chemical disequilibrium, the simultaneous presence of significant amounts of both oxygen and methane for example, may be difficult to achieve (a somewhat more nuanced consideration is that the level of methane in our atmosphere today would be difficult to see with planned space-based telescopes). Exoplanets in an atmospheric state similar to Earth’s middle chapters may be most problematic to characterize, with both low oxygen and low methane (a chemical consequence of the sulfate-rich character of the Proterozoic oceans). Inhabited planets

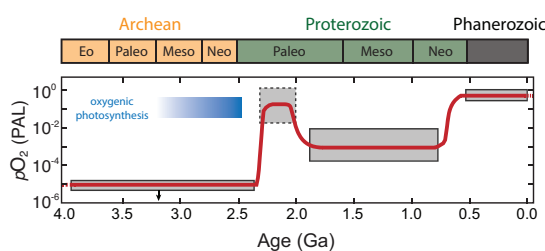


Figure 5. Evolution of Earth’s atmospheric O₂ content through time. Shaded (credit: doi.org/10.1089/ast.2017.1729).

with non-detectable biosignatures have been proposed as potential ‘false negatives’ for remote life detection. However, even the low oxygen world of the Proterozoic may have generated enough ozone to create a notable spectral impact—if a future telescope is designed to look in the ultraviolet portion of the planet’s spectrum (Figure 6). Continued exploration of the geochemical and atmospheric evolution of our own worlds will provide novel insights into the search for life elsewhere and will steer fundamental decisions about the designs of future telescopes.

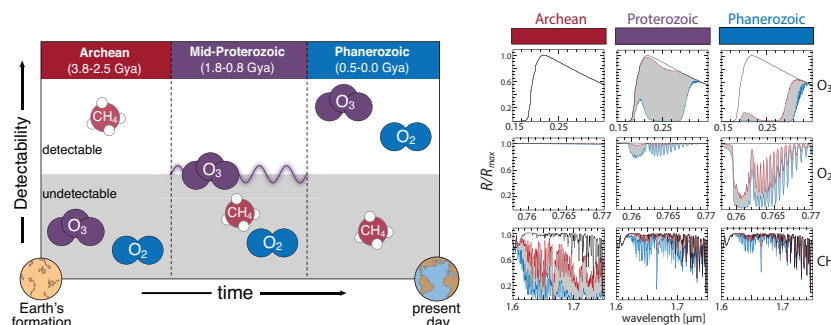
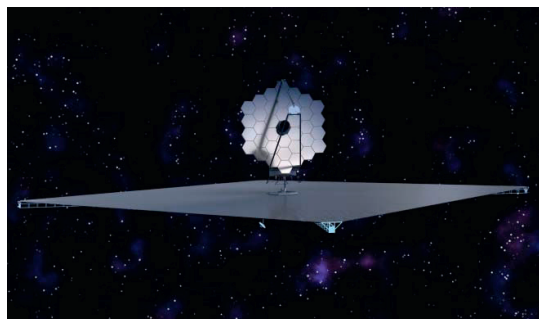


Figure 6. Left panel: conceptual illustration of O₂, O₃ and CH₄ detectability in the UV, Vis/NIR and MIR through Earth history. Right panel: spectral features of O₂, O₃ and CH₄ in the UV, Vis/NIR and MIR throughout geologic time. (Image credit: doi.org/10.1089/ast.2017.1729).

Prospects for answering the question “are we alone?”

The discovery of exoplanets will continue unabated, with evidence gathered by both observatories on the ground and in space, such as the recently launched Transiting Exoplanet Survey Telescope (TESS). Most of these discoveries will be made either by the periodic dimming of light as the planet crosses between us and its star (transit photometry, as is used by TESS) or by the characteristic ‘wobble’ of a star induced by the gravitational tugs of a planet and revealed by extremely slight changes in that star’s colour spectrum (known as the Doppler radial-velocity method, employed by large ground-based observatories). A select few of these worlds will have a size and mass comparable to Earth and will orbit within the habitable zones of stars close enough to characterize using near-future observatories.

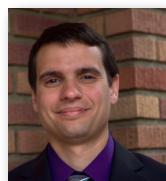
Figure 7. A conceptual image of the proposed LUVOIR telescope, which would be capable of collecting spectra of planets orbiting within the habitable zone of nearby stars (credit: NASA/GSFC/JPL/STScI)



The James Webb Space Telescope (JWST), now set to launch in 2021, may be our first chance to probe the atmospheres of many rocky exoplanets through transit spectroscopy (observing the colours of light filtered through the exoplanet's atmosphere while it is in transit). JWST is unlikely to find oxygen or ozone, simply because of the properties and sensitivity of the instruments onboard. However, it could find Archean-like biospheres rife with methane. This methane, if combined with carbon dioxide, may indicate a form of chemical disequilibrium suggestive of life. Even more powerful space-based observatories optimized for exoplanet research are currently in their science and technology design phases. One such concept is the Large Ultraviolet Optical Infrared Survey Telescope (LUVOIR), an orbiting telescope with an 8–15 metre

mirror capable of directly imaging dozens of Earth-like planets around nearby stars with the capacity to detect biosignature gases like oxygen and ozone (by comparison, Hubble's mirror diameter is 2.4 meters). A similar concept is the Habitable Exoplanet Observatory (HabEx), a smaller (4–6 metre mirror) mission that would focus on characterizing the nearest exoplanets to our solar system. A flagship mission like LUVOIR or HabEx, with a hypothetical launch window in the mid-2030s, has been endorsed by the National Academy of Sciences in its recent report on 'Exoplanet Science Strategy.' The ultimate success of these missions may be determined by upcoming advances in coronagraphs and starshades, two different technologies for 'nulling' or cancelling the light of an exoplanet's host star so the much dimmer planet can be seen directly via reflected light.

In addition to technical advancements, ongoing theoretical studies are assembling comprehensive libraries of potential biosignatures (many of which may differ from what we find on Earth), including efforts to identify 'false positives'—that is, abiotic processes that can generate the same compounds. In the coming decades, we will be able to determine whether global biospheres like Earth's are common or rare in the universe. We are indeed living in a thrilling era of discovery. ■



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Timothy Lyons is a distinguished professor at the University of California, Riverside, and the Principle Investigator of the NASA Astrobiology Institute's Alternative Team. Lyons is a field and laboratory geochemist whose research explores the evolving ocean and atmosphere and their cause-and-effect relationships with the origin and evolution of life. He uses insights gained from studying the geochemical archive of Earth history to inform the possible range of geologic, chemical and atmospheric states of rocky exoplanets.
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Christopher Reinhard is an Assistant Professor at the Georgia Institute of Technology and a member of the NASA Astrobiology Institute's Alternative Earths Team. Reinhard's research focuses primarily on understanding the biological factors that control planetary evolution and in particular the mechanisms that regulate the emergence and maintenance of atmospheric biosignatures.
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Further reading

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