Understanding planetary context to enable life detection on exoplanets and test the Copernican principle

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The search for life on exoplanets is motivated by the universal ways in which life could modify its planetary environment. Atmospheric gases such as oxygen and methane are promising candidates for such environmental modification due to the evolutionary benefits their production would confer. However, confirming that these gases are produced by life, rather than by geochemical or astrophysical processes, will require a thorough understanding of planetary context, including the expected counterfactual atmospheric evolution for lifeless planets. Here, we evaluate current understanding of planetary context for several candidate biosignatures and their upcoming observability. We review the contextual framework for oxygen and describe how conjectured abiotic oxygen scenarios may be testable. In contrast to oxygen, current understanding of how planetary context controls non-biological methane (CH\textsubscript{4}) production is limited, even though CH\textsubscript{4} biosignatures in anoxic atmospheres may be readily detectable with the James Webb Space Telescope. We assess environmental context for CH\textsubscript{4} biosignatures and conclude that abundant atmospheric CH\textsubscript{4} coexisting with CO\textsubscript{2} and CO:CH\textsubscript{4} \ll 1 is suggestive of biological production, although precise thresholds are dependent on stellar context and sparsely characterized abiotic CH\textsubscript{4} scenarios. A planetary context framework is also considered for alternative or agnostic biosignatures. Whatever the distribution of life in the Universe, observations of terrestrial exoplanets in coming decades will provide a quantitative understanding of the atmospheric evolution of lifeless worlds. This knowledge will inform future instrument requirements to either corroborate the presence of life elsewhere or confirm its apparent absence.
planet atmospheres to determine how to distinguish biological and abiotic CH₄. Finally, we argue that comparable context-dependent approaches could be applied to other biosignatures. Our focus is on atmospheric biosignatures, given their imminent observability, but a similar contextual approach may be applied to surface or temporal biosignatures⁹,10.

Oxygen as a case study in contextual arguments for life

Molecular oxygen (O₂), or its photochemical by-product ozone (O₃), was considered a promising potential biosignature long before the discovery of exoplanets⁸,¹¹. Arguments for oxygen as a biosignature can be boiled down to two premises. First, regardless of specific biochemical, any surface life that develops the capacity for oxygenic photosynthesis will possess an immense evolutionary advantage over other energy metabolisms. Chemotrophic life depends on geochemical sources of free energy and anoxygenic photosynthesis is similarly limited by the availability of electron donors such as H₂ or Fe²⁺. In contrast, oxygenic photosynthesis requires only water and carbon dioxide (CO₂), substrates that are virtually unlimited on planets with habitable surfaces:

\[
\text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{CH}_3\text{O} + \text{O}_2 \tag{1}
\]

Second, non-biological production of large amounts of oxygen is unlikely. This second premise has received considerable attention in the astrobiology literature, to the point where there are now detailed reviews assessing scenarios for non-biological oxygen production, their plausibility and possible contextual clues to establish biogenicity (or lack thereof)⁹. While understanding of atmospheric oxygenation remains incomplete, oxygen is the best studied example of how to assess biosignatures through planetary context. Much of the focus has so far been on so-called photochemical oxygen false positives. The photodissociation of oxygen-bearing molecules such as CO₂ can, in principle, result in steady-state atmospheres rich in O₂ or O₃ (refs. ¹³–¹⁵). The viability of photochemical oxygen production depends on the spectral energy distribution of the host star, as well as on catalytic recombination processes in both the atmosphere and on the surface¹⁶–¹⁸. Such photochemically produced O₂ may be diagnosable from the presence or absence of other atmospheric constituents (for example CO), as well as from the stellar context¹¹.

The ways in which broader planetary context controls the long-term build-up of oxygen due to slight imbalances in sources and sinks is less understood. Oxygen build-up on planets around low mass stars due to extensive hydrogen escape during the pre-main sequence has been suggested¹⁹, and coupled models have explored whether such oxygen build-up could overwhelm magma ocean sinks²¹–²³. The possibility of oxygen accumulation due to water loss in atmospheres with low non-condensable inventories has also been proposed²⁴–²⁵. In general, however, understanding of whole-planet redox evolution remains rudimentary and untested.

Krissansen-Totton et al.²⁶ modelled the evolution of whole planetary contexts, from magma ocean to temperate geochemical cycling, with the goal of anticipating non-biological oxygen accumulation. The model attempts to include all non-biological processes that add or remove oxygen from the atmosphere. The thermal evolution of the interior is explicitly coupled to surface volatile evolution to self-consistently model outgassing and other crustal–atmosphere exchange processes. While lifeless Earth twins are not predicted to possess oxygen-rich atmospheres in this framework, several scenarios were identified whereby oxygen could build up to detectable levels without life if initial volatile inventories differed dramatically from that of Earth (Fig. 1). Crucially, such whole-planet modelling can help identify the contextual observations required to rule out non-biological oxygen. For example, terrestrial planets with large water inventories (tens to hundreds of Earth oceans) will rapidly cease to produce new crust due to the pressure overburden of the surface ocean²⁷,²⁸. This inhibits all oxygen sinks such as magmatic outgassing and serpentinization since these processes are limited by fresh crustal production, and this, in turn, allows for long-term oxygen accumulation via hydrogen loss to space²⁹,³⁰. While the precise water inventory threshold for oxygen sink suppression is fuzzy, this conclusion is qualitatively insensitive to crustal composition, mantle redox or tectonic regime³¹. Fortunately, since tens of Earth oceans are required in this scenario, the presence of any subaerial land would preclude the water depths³² required for waterworld false positives. Time-resolved photometry could be used to detect such an ocean–land dichotomy to rule out waterworld oxygen false positives³³–³⁵.

While many simplifying assumptions are necessary, such models can be used to begin mapping out the likelihood of non-biological oxygen production as a function of astrophysical variables, such as planet–star separation, stellar age and initial volatile inventories and so on. (Fig. 2). These statistical relationships could be validated with future instruments.

Observational prospects for O₂ biosignatures in the 2020s

Biogenic oxygen will probably not be accessible to JWST for known targets³⁶–³⁸. Although biological oxygen detection might be possible with high-resolution spectrographs from the ground-based Extremely Large Telescopes³⁹–⁴¹, this will require many coadded transits. Nevertheless, JWST will allow coupled models of planetary atmosphere–interior evolution to be tested and validated. Excessive non-biological oxygen build-up on highly irradiated planets (tens to hundreds of bars of O₃) could be observable with JWST⁴²–⁴⁴, and so the presence or absence of oxygen on highly irradiated planets may directly constrain escape physics and surface–atmosphere interactions. If the TRAPPIST-1 planets⁴¹ and other highly irradiated terrestrials have atmospheres, then a many-transit deep dive with JWST⁴⁵ to constrain their compositions would be extremely valuable for interpreting any future oxygen detections on habitable zone planets with next-generation instruments.

A timely return to Venus will also provide critical information for any future exoplanet oxygen detections. Venus's modern atmosphere contains virtually no O₂, despite D/H ratios suggestive of excessive water loss³⁶. Understanding Venus's climate evolution, particularly the fate of water and oxygen, is a prerequisite for interpreting oxygen on potentially habitable exoplanets. Observations of surface mineralogy, trace gas inventories, and tectonic recycling with the upcoming DAVINCI⁴⁴, VERITAS⁴⁵ and EnVision⁴⁶ missions could dramatically improve constraints on crustal oxygen sinks and atmospheric escape physics. Venus is, after all, the only other Earth-sized planet accessible to in situ analysis, and thus presents a unique opportunity to advance understanding of soon-to-be-observed terrestrial exoplanets.

CH₄ biosignatures and early Earth analogues

While oxygenic photosynthesis seems like the logical evolutionary endpoint to oxygen-respiring heterotrophs, there is no guarantee that oxygen-rich atmospheres are ubiquitous, even if life is common. Oxygenic photosynthesis could have been a one-off evolutionary event not frequently repeated, or oxygen-rich atmospheres may not easily accumulate³⁷. This motivates the search for alternative biosignatures. In this context, the history of atmospheric modification by life on Earth is a useful guide (Fig. 3).

The CH₄ in Earth's atmosphere today, and indeed throughout Earth history, is overwhelmingly biogenic, produced by methanogenic microbes through these net reactions:

\[
\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O} \tag{2}
\]

\[
\text{CH}_3\text{COOH} \rightarrow \text{CH}_4 + \text{CO}_2
\]

\[
\text{CH}_4 + \text{CO}_2 \rightarrow \text{CH}_3\text{O} + \text{O}_2
\]
Even CH$_4$ that is not directly produced by life is typically a by-product of the degradation of organic matter from previously living organisms (thermogenic CH$_4$). The dominance of biological CH$_4$ sources has led to the suggestion that abundant CH$_4$ could be a sign of life elsewhere, perhaps an indicator of early Earth-like biospheres$^{48-52}$. Recalling life’s universal need for free energy to sustain a far-from-equilibrium state, there is also a strong evolutionary incentive for methanogens to proliferate due to the probable ubiquity of the necessary substrates, CO$_2$ + H$_2$, as common outgassing products. Indeed, methanogenesis seems to have emerged easily and early in Earth’s evolution$^{53,54}$. Naturally, the mere presence of methanogenic life does not guarantee detectable atmospheric CH$_4$; low nutrient availability, small H$_2$ degassing fluxes or limited surface habitability could result in false negatives. Nevertheless, ecosystem modelling of diverse chemotrophic and anoxygenic photosynthesizing biospheres provides numerous plausible scenarios for biogenic, CH$_4$-rich atmospheres$^{55-57}$.

Methane is a more compelling biosignature when found in combination with CO$_2$ alongside the absence or low abundance of carbon monoxide (CO)$^{58}$. The combination of CH$_4$ and CO$_2$ represents carbon in its most reduced and most oxidized forms, respectively, which is hard to explain without life$^{59}$ (Fig. 4a). Moreover, in terrestrial planet atmospheres, CH$_4$ has a short photochemical lifetime, and thus high abundances require substantial replenishment fluxes$^{60,61}$. Assessment of the biogenicity of CH$_4$ in terrestrial planet atmospheres therefore depends on whether, and in what contexts,
it could be produced in large quantities without life. None of the most obvious non-biological replenishment processes can plausibly maintain abundant CH$_4$ + CO$_2$ without also producing abundant CO (Fig. 4). For example, magmatic outgassing sufficiently reducing to produce CH$_4$ would also generate large accompanying fluxes of CO (ref. 59) (Fig. 4b), and for strongly reduced magma compositions, CH$_4$ would probably not outgas to any appreciable extent due to graphite saturation. Similarly, CH$_4$ produced continuously via impacts requires excessive impactor fluxes and is also expected to generate abundant CO (ref. 50) (Fig. 4c). Very large impacts can produce transient (roughly million year) CH$_4$-rich atmospheres, but such atmospheres are typically H$_2$-dominated and could therefore be identified via low mean molecular weight$^{60}$. Serpentinization and Fischer–Tropsch type reactions are perhaps the most plausible mechanisms for generating a CH$_4$ false positive (Fig. 4d), but in this case the CH$_4$ flux is limited by the supply of fresh crust and by the efficiency of conversion from H$_2$ to CH$_4$. On the modern Earth, serpentinization fluxes of CH$_4$ at mid-ocean ridges and subduction zones are around 2–3 orders of magnitude lower than the global biological flux due to these supply limits$^{61-63}$. Although this flux could

Fig. 2 | Time evolution of atmospheric O$_2$, CO$_2$ and H$_2$O vapour as a function of planet–star separation for a sample of simulated lifeless planets. The colour scale shows the mean surface temperature, and the black dashed line shows the runaway greenhouse limit for an Earth-like albedo, which evolves with stellar luminosity (a G star is assumed). Squares denote non-zero surface liquid water inventories, whereas circles show model runs with uninhabitable surface conditions. Each row shows the atmospheric composition at a different time in the main-sequence lifetime (see Supplementary Video 1 for an animation). The simulated planet population, taken from ref. 26, has a wide range of initial volatile inventories and parameter values that govern atmosphere–interior exchange of volatiles. Models such as this can be used to predict trends in non-biological oxygen accumulation alongside their contextual clues. The grey shaded regions denote numerical limits; lower abundances may be realized but fluxes cut off here for numerical efficiency.
be higher on planets with greater crustal production and more efficient catalysis of abiotic CO₂ reduction, the likelihood of producing abiotic fluxes comparable to Earth’s biological production is still low⁵⁸. Volatile-rich objects (for example Titan-like compositions) may retain sizeable primordial reservoirs of CH₄ and CO₂ in their icy interiors⁶⁴ (Fig. 4e), but such CH₄ would not persist for more than ~10⁷–10⁸ years at habitable zone planet–star separations⁶⁵, and these planets could also be identifiable via their anomalously low densities. Exploration of these conspicuous scenarios (Fig. 4) is a first step towards a contextual framework for CH₄ biosignatures, including the identification of observational clues for disentangling biological CH₄ from non-biological processes. However, many other geochemical reactions and geophysical processes have been conjectured to contribute to abiotic H₂ production on Earth⁶⁶, and while such fluxes are negligible compared with that of Earth’s biosphere, understanding these proposed mechanisms and extrapolating them to other planetary environments, compositions and tectonic regimes remains an underexplored area of astrobiological research.

Note that while abundant CO is generated by many of the non-biological processes in Fig. 4, abundant CO is generally not expected on inhabited planets due to CO being a readily consumed source of free energy for microorganisms⁶⁷,⁶⁸. This CO biosignature argument is complicated by the fact that biospheres dominated by oxygenic photosynthesis could produce high CO fluxes via biomass burning, and that even anoxic biospheres may produce some CO due to incomplete conversion of CO to CH₄ (refs. ⁵⁵,⁶⁷). Further ecosystem modelling is required to determine the range of CO₃, CH₄ and CO abundances expected for different biospheres and stellar types, but current ecosystem modelling shows that CH₄/CO ratios ought to be high on inhabited planets⁵⁵–⁶⁷, perhaps suggesting that the relative abundance of CH₄/CO could help distinguish non-biological CH₄ from metabolism⁶⁵.

**Observational prospects for CH₄ biosignatures in the 2020s**

Theoretical understanding of CH₄ biosignatures and their false positives may soon lag behind observational capabilities. It is worth noting that CH₄ biosignatures are potentially detectable with JWST⁶⁹,⁷⁰, with simulated retrievals suggesting that biogenic CH₄ on TRAPPIST-1e, 1f and 1g may be detectable with approximately 10 transits with NIRSpec prism (Fig. 5). There are even claims of CH₄ detections with existing instruments for the highly irradiated terrestrial planet GJ 1132b⁷¹, although the proposed outgassing mechanism is improbable as it does not account for graphite saturation under reducing conditions⁶⁵, and a featureless spectrum has been suggested by independent analyses of the same Hubble data⁷²,⁷³. Methane may also be detectable indirectly via organic haze features in high CH₄/CO₂ atmospheres⁷⁴.

What are the prospects for interpreting near-term CH₄ detections as biogenic—or, in other words, could life be confirmed on an Archaean Earth analogue such as that depicted in Fig. 4a?
Although CO₂ detections and crude constraints on CO abundances may be possible⁴⁴, unambiguously ruling out high CO/CH₄ ratios consistent with abiogenic processes will require many transits (Fig. 5). More fundamentally, JWST will not provide sufficient information on planetary context to fully assess habitability. For example, water vapour is probably inaccessible to transit observations due to cloud condensation⁴³, and so JWST will be unable to assess the surface conditions on planets with CH₄ detections. With that said, the detection of abundant CH₄ in terrestrial planet atmospheres with JWST would be tantalizing, especially alongside CO₂ and with a high CH₄/CO ratio. Such a detection, while not definitive, would undoubtedly motivate the development of future instruments to better characterize planetary context and look for corroborating evidence for a biosphere.

**Alternative and agnostic biosignatures**

Whereas the direct products of energy metabolism, such as O₂ and CH₄, are broadly appreciated as promising context-dependent biosignature gases, there is a growing literature on ‘alternative’ biosignatures. These include other gaseous by-products of metabolism, surface pigments such as the vegetative red edge⁷⁵–⁷⁷, temporal variations in gaseous or surface features indicative of a productive biosphere⁴, or agnostic biosignatures that are not specific to particular underlying biochemistries but instead invoke generalizable thermodynamic or informational properties of life⁸⁴–⁸⁶.

Virtually all of these potential signs of life are dependent on the whole-planet context: both the evolutionary incentive for their production and the likelihood of non-biological false positives need to be considered. For example, nitrous oxide (N₂O) is not a direct product of energy metabolism, but is instead a by-product of incomplete denitrification (the reduction of nitrate to molecular nitrogen). If life elsewhere actively cycles nitrogen, which seems probable given the importance of nitrogen to many organic molecules⁸¹, then the short photochemical lifetime of N₂O makes it a promising biosignature gas⁴. With that said, there are non-biological mechanisms for generating N₂O via particle-flux-induced atmospheric chemistry⁸² or even via abiogenic iron oxidation in hypersaline cold environments⁸³. Thus, any assessment of N₂O biogenicity will require constraints on the planetary and stellar context, including an assessment of plausible non-biological fluxes. Similar contextual considerations apply to almost all other gaseous and surface biosignatures that have been proposed. Methyl chloride (CH₃Cl) is a by-product of metabolism⁸⁴, but is also potentially produced via metamorphism of organic matter and evaporites⁸⁵ or via volcanic degassing⁸⁶. Phosphine (PH₃) may also be a by-product of metabolism in oxidizing atmospheres, whereas its formation in deep, H₂-dominated atmospheres is thermodynamically favoured⁸⁷. Seasonal variation in atmospheric O₂ or CO₂ could be biologically driven, but climate–photochemical variations must be ruled out⁴.

With that said, there are some molecules with formation pathways so thermodynamically improbable that their presence in exoplanet atmospheres in high abundances is extremely unlikely to be attributable to non-biological processes, regardless of the planetary context. Such context-independent biosignatures are more analogous to the kinds of unambiguous in situ Solar System biosignatures discussed above, since they provide direct access to thermodynamic structures and evolutionary properties of life. Technosignatures such as industrial waste products (for example chlorofluorocarbons) fall into this category, as may complex organic molecules such as isoprene⁸⁸ and organo-sulfur compounds such as dimethyl sulfide⁸⁹.
Habitability must be confirmed through positive scenarios in Fig. 4. However, these observations are necessary, but insufficient, to determine biogenicity if an Archaean earth-like scenario is conceivable that photochemical feedbacks and efficient oxidation of biogenic CH4 in the oceans kept both O2 and CH4 abundances, which would be serendipitous and probably short-lived without carefully tuned Gaian feedbacks. The metabolic incentive to produce the abovementioned alternative biosignature gases in H2-dominated atmospheres is also unclear.

In addition to considering standalone biosignatures, the limitations of N=1 Earth life have motivated explorations of more generalized life metrics that are (ideally) independent of underlying biochemistry, or that make no assumptions about specific metabolisms. Atmospheric chemical disequilibrium has long been debated as a potentially more universal sign of life\textsuperscript{87–91}. The coexistence of O2 and CH4 is certainly a more compelling biosignature than either species alone, due to the short photochemical lifetime of CH4 in O2-rich atmospheres, which would imply high replenishment fluxes for both species that are unlikely to be non-biological. Similarly, as discussed above, the coexistence of CH4 and CO2 is a form of disequilibrium biosignature, although here the argument is focused less on photochemistry than on the redox state of the interior and the low likelihood of large fluxes of both the most oxidized and reduced forms of carbon without biological catalysis.

Fig. 5 | Detectability of biogenic CH4 with JWST. Simulated ten-transit retrieval of an Archaean Earth-like TRAPPIST-1e (Fig. 4a). a. Simulated noisy transmission spectrum (red) alongside the retrieved spectrum (black) with the 95% credible interval shaded blue. b–e. Posterior mixing ratios for CH4 (b), CO2 (c), CO (d) and CO/CH4 (e), respectively (the 66% confidence interval is shown by the dashed black lines) alongside true synthetic abundances (blue lines). The retrieved mixing ratios with 1σ uncertainties are included at the tops of the panels, where f is the mixing ratio of the indicated species. Biogenic CH4 is detectable, and the CH4, CO2, and CH4 abundances are sufficiently constrained to disfavour the false positive scenarios in Fig. 4. However, these observations are necessary, but insufficient, to determine biogenicity if an Archaean Earth-like scenario such as Fig. 4a is encountered. Habitability must be confirmed through other means, since atmospheric water vapour and surface properties are inaccessible to JWST transit observations. Figure adapted with permission from ref.\textsuperscript{101}, IOP Publishing.

(while isoprene has never been detected on Titan and is not a predicted photochemical product\textsuperscript{90}, the presence of propadiene\textsuperscript{90} suggests that abiotic isoprene synthesis—albeit with trivial fluxes—is not completely implausible.) The obvious disadvantage to these biosignatures is that they are not direct products of energy metabolism but are instead incidental by-products of secondary metabolic processes. As such, they may be specific to Earth life, and the likelihood of large fluxes is challenging to assess. Moreover, greater molecular complexity is typically associated with shorter photochemical lifetimes, leading to poor detectability prospects unless biogenic fluxes are extreme. Isoprene and dimethyl sulfide are also challenging to separate spectroscopically from other hydrocarbons\textsuperscript{90}. Although more context-independent biosignatures could provide a shortcut to definitive life detection on exoplanets, the chances of success for any particular biosignature are arguably slim as there is no clear metabolic or evolutionary incentive for biospheres to produce such molecules in detectable quantities.

In fact, the near-term (~10 yr) detectability prospects for the alternative biosignature gases described above are almost universally bleak\textsuperscript{42,84,91}. One possible exception is within extended H2-dominated atmospheres, where the detectability of N2O, CH4, Cl dimethyl sulfide, PH3 and isoprene is enhanced\textsuperscript{92,93}. The habitability of H2-dominated atmospheres has long been a subject of speculation\textsuperscript{84,85}, but these environments remain deeply unfamiliar planetary contexts. Unlike in high-mean-molecular-weight terrestrial atmospheres where silicate weathering feedbacks seemingly stabilize surface habitability against stellar evolution\textsuperscript{86,87}, no plausible geochemical feedback mechanism has been proposed for maintaining temperate climates on H2-rich worlds; surface habitability would be serendipitous and probably short-lived without carefully tuned Gaian feedbacks\textsuperscript{88,91}. The metabolic incentive to produce the abovementioned alternative biosignature gases in H2-dominated atmospheres is also unclear.

If focusing attention on individual biosignature gases central to energy metabolism (for example O2, CH4) is a top-down approach to biosignatures, then a complementary bottom-up approach would be to systematically characterize all small molecules that could conceivably be produced by life\textsuperscript{92,93}. This exhaustive method is more agnostic to underlying biochemistry, and may uncover thermodynamically improbable complex molecules that require less contextual information to be deemed biogenic. On the other hand, this ‘all small molecules’ approach necessitates a huge investment of effort to determine the thermodynamic, kinetic and radiative properties
of candidate molecules, many of which lack an obvious evolutionary incentive for planetary-scale biological synthesis—not to mention the work required to characterize their false positives within plausible planetary contexts. Both top-down and bottom-up approaches can yield valuable insights, but given the incomplete contextual understanding and imminent detectability of the biosignature gases central to carbon-based energy metabolism (that is $O_2$ via equation (1) and $CH_4$ via equation (2)), we favour prioritizing an improved understanding of these biosignatures and their false positives.

Alternative ideas for agnostic biosignature metrics include the chemical network properties of atmospheres modulated by life$^{79,106,107}$, where network connectivity or complexity is envisaged as a sign of life independent of specific biochemistry. For all proposed agnostic biosignatures, characterizing the planetary context remains a necessary step for assessing biogenicity; interpretation of atmospheric disequilibrium or network properties will require both an evaluation of how these metrics apply to uninhabited worlds as well as the expected modification by biospheres.

(When) will exoplanet life detection be definitive

Barring the lucky detection of complex, high-sensitivity molecules, corroborating context-dependent exoplanet biosignatures will be a gradual process. The possibility of false positives for metabolic products such as $O_2$ and $CH_4$ implies that multiple independent lines of evidence for life may be required for a definitive assessment. For example, the detection of gaseous biosignatures in combination with temporal variations indicative of seasonal metabolic activity alongside reflectance spectra suggestive of surface pigmentation would provide a detailed picture of the planetary context that is challenging to explain without modification by Darwinian processes; non-biological explanations would require an ever-increasing number of ad hoc assumptions.

JWST and the ground-based Extremely Large Telescopes will not have the capabilities to provide such compelling evidence for life. However, they could make the first tentative detections of potential biosignature gases such as $CH_4$ and, more importantly, they will provide an invaluable opportunity to test conceptual frameworks for how terrestrial planets evolve. For example, JWST observations of highly irradiated terrestrial planets will constrain the likelihood of non-biological $O_2$ accumulation on more temperate planets. Crucially, these observations will lay the groundwork for more expansive searches for life with next-generation telescopes designed with capabilities to constrain the planetary context such that genuine biosignatures and lifeless evolution can be disentangled.

Looking ahead to these future missions, it is worth considering the possible outcomes. If no biosignatures are detected across a large sample of terrestrial planets, and if false negatives can be largely ruled out$^{107}$, then it may be safe to conclude that productive surface biospheres are uncommon. Moreover, if the ostensible habitability of these uninhabited planets can be confirmed$^{34}$, then the most probable explanation for Earth’s uniqueness would be that the origin of life was improbable. The second possible outcome is that multiple independent lines of evidence for life emerge—perhaps even on multiple planets—for which there is no plausible non-biological explanation. In this case, the Copernican Principle will have been reaffirmed beyond reasonable doubt. The third possibility is that the evidence for life on exoplanets remains ambiguous. The limited information gleaned from remote observations and degeneracies in validated models of terrestrial planet evolution could lead to a situation in which the biogenicity of observed planetary environments remains debatable, even with next-generation telescopes such a flagship direct-imaging mission$^1$. Even in this scenario, however, new-found quantitative understanding of terrestrial planet evolution could be leveraged to determine what new observations would be required to resolve the ambiguities. There is no shortage of plausible concepts for future telescopes with degeneracy-breaking capabilities, such as the ability to detect trace biosignature gases and their isotopes, or even resolve planetary surfaces$^{110-112}$. In short, constraining the abundance of life in the Universe will be possible via astronomical observations, but there is insufficient understanding of how much we need to know about the planetary context to be definitive. The search for life elsewhere could be over soon, or it could take generations, depending on both the resources dedicated to the effort, and the as-yet unknown diversity and complexity of uninhabited worlds that exist in nature.

Conclusions

• The discovery of life on exoplanets, if this occurs, will probably not be a moment in time. It will instead involve years or even decades of debate, with multiple observations and instruments leveraged to resolve ambiguities. No single molecule or surface feature is likely to provide definitive evidence, and multiple lines of evidence may be required to rule out false positives.

• Robust life detection will only be possible if testable models of terrestrial planet evolution are developed and validated against a population of lifeless terrestrial planets. This understanding of planetary context will be necessary to confidently rule out non-biological scenarios.

• Oxygen is the model biosignature molecule for this contextual approach. Theoretical progress has been made and model predictions for non-biological oxygen accumulation will be testable in the JWST era. Many uncertainties remain, however, especially relating to atmospheric escape physics, planet formation and surface-atmosphere interactions.

• For many other potential biosignature gases, understanding of planetary context is lagging behind observability. This is particularly true of $CH_4$, which may be readily detectable with JWST and yet false positive scenarios have not been thoroughly explored. Preliminary investigations of magmatic outgassing, hydrothermal systems and impacts suggest that abundant atmospheric $CH_4$ coexisting with $CO_2$ and limited $CO$ is hard to explain without life, but future study ought to develop coupled geochemical evolution models of a planet’s mantle and crust to self-consistently predict volatile fluxes from both high- and low-temperature systems, such that the contextual clues of non-biological $CH_4$ can be predicted.

• Although ambiguities may persist into the space-based direct-imaging era, whole-planet frameworks can be leveraged to determine what contextual observations need to be pursued with future instruments.

Data availability

The data outputs from Supplementary Video 1 are available at https://doi.org/10.5281/zenodo.5719456.

Code availability

The Python code for our atmosphere evolution model is open source and available at https://doi.org/10.5281/zenodo.4539040.

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Author contributions

J.K.T. designed and directed the study, M.T. contributed the CH₄ biosignature analysis, M.L.G. performed the O₂ false positive calculations and J.J.F. supervised the study. All authors contributed to drafting and editing the manuscript.

Competing interests

The authors declare no competing interests.

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