Astro2020 Science White Paper

Life Beyond the Solar System: Remotely Detectable Biosignatures

Thematic Areas: ☒ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract:

This white paper reviews the scientific community's ability to use data from future telescopes to search for life on exoplanets, summarizing products from the Exoplanet Biosignatures Workshop Without Walls (EBWWW). The EBWWW was a series of online and in-person activities, with participation from the international exoplanet and astrobiology communities, to assess state of the science and future research needs for the remote detection of life on planets outside our Solar System. These activities culminated in five published manuscripts:

1. A review of known and proposed biosignatures (Schwieterman et al., 2018)
2. A review of the O_2 biosignature as an end-to-end example of the contextual knowledge required to rigorously assess any claims of life on exoplanets (Meadows et al., 2018)
3. A generalized statistical approach to place qualitative understanding and available data in a formal quantitative framework according to current understanding (Catling et al., 2018)
4. Identification of needs to advance that statistical framework, and to develop or incorporate other conceptual frameworks for biosignature assessment (Walker et al., 2018)
5. Review of the upcoming observatories – both planned and possible – that could provide the data needed to search for exoplanet biosignatures (Fujii et al., 2018).

This is an updated version of a white paper that was submitted to National Academy of Sciences (NAS) Exoplanet Science Strategy (ESS) and the NAS State of Science of Astrobiology (SSA) committees. The NAS ESS and SSA reports successfully accounted for the contents of the prior white paper; here we provide updates and re-frame the content for the NAS Astro2020 White Paper call.

1 Introduction

For the first time in human history, we have the ability to apply the scientific method to the question "Does life exist beyond our Solar System?" Rapid advances in exoplanet discovery, planetary systems science, and technology have made this an achievable endeavor that we can embark upon with observatories being considered by the Astro2020 Decadal Survey. This presents an opportunity that is not once-in-a-lifetime, but once-in-a-civilization. Readers of this white paper could be among the first scientists to collect data demonstrating the presence of a second global biosphere, and no matter the results, this search will re-shape our view of humanity's place in the cosmos. A rapidly growing community of international and interdisciplinary scientists and engineers is ready to overcome the challenges that stand in the way of realizing this moment's potential. Here, members of that community outline and review the science of biosignatures for the Astro2020 era, and discuss the programs and projects required to take the next leap.

2 Progress in the "New Worlds, New Horizons" Era

2.1 Expanding the library of signs of life

Analyses of a exoplanet's spectrum, even from a single spatial element, can yield information on the presence or absence of chemicals, allowing proposed biosignatures and other features of the planet's environmental context to be identified. Much of the history of remote detection of biosignatures has focused on spectral features of specific biological byproducts or global phenomena resulting from life. A review of exoplanet biosignatures is presented in Schwieterman et al. (2018), updating a prior review by Des Marais et al. (2002). There have been four major developments in exoplanet biosignature science since Astro2010: 1) the generation of a broader list of potential biosignatures; 2) more comprehensive simulations of these signatures in the context of planetary environments; 3) consideration of abiotic means through which these signatures could be generated on both living and non-living worlds; and 4) a recognition that our determination of the presence of life on an exoplanet must be quantified, and associated uncertainties must be understood.

2.2 Novel candidate biosignatures

There has been a large expansion of the library of proposed biosignatures. Photosynthetic pigments have been discovered that extend the wavelengths of light that can drive oxygenic photosynthesis (Ho et al. 2016; Li et al., 2015), increasing the star-planet combinations that can sustain this metabolism (Takizawa et al., 2017). Other types of surface pigments have also been considered, including bacteriorhodopsin and other pigments (e.g., Schwieterman et al., 2015a, Hegde et al., 2015). For atmospheric biosignatures, several thousand biogenic gases have been identified as worthy of further consideration (Seager et al., 2016). On planets lacking oxygen, organic hazes have also been identified as possible signs of life (Arney et al., 2016). Sustained formal efforts to catalog and screen of new proposed biosignatures and are critically needed.

2.3 3D simulation of living worlds

Advanced modeling tools are critical for simulating biosignatures on a global scale. These include photochemical and climate models that can self-consistently simulate these biosignatures within their planetary context. A significant recent advance in this area is the utilization of 3-dimensional (3D) spectral models (e.g., Robinson et al., 2011; Schwieterman et al., 2015b). In addition, 3D general circulation models (GCMs) are emerging as important theoretical tools to explore the dynamics of planetary climates and to expand conceptualization of the habitable zone (HZ; e.g., Turbet et al.2016; Way et al., 2017; Del Genio et al., 2019). Further development of these modeling capabilities will be needed to apply coupled biosphere-atmosphere processes to simulate biosignatures in a planetary systems science context. One critical development will be the proliferation of GCMs that include photochemistry for biosignature assessment (Chen et al., 2018). Careful quantitative evaluation of potential seasonal/temporal biosignatures will be particularly dependent on the development of coupled 3D photochemical-climate models (Olson et al., 2018).

2.4 The importance of environmental context

Oxygen-based biosignatures (O_2 and/or O_3) are extremely promising, as they fulfill the three major requirements of a robust atmospheric biosignature: (1) reliability; (2) survivability; and (3) detectability. However, a number of potential ”false positives” for O_2/O_3 biosignatures exist, rendering additional environmental context critical for interpreting oxygen-based biosignatures. For example, information about the host star (spectral type, age, activity level), major planet characteristics (size, orbit, mass), and accessory atmospheric species (H_2O, CO_2, CO, CH_4, N_4) can all help to diagnose abiotic O_2/O_3 in an atmosphere.

Careful selection of targets can help mitigate against the likelihood of false positive O_2/O_3 signals. For example, selection of older F, G, K or early M dwarf targets (M0-M3) would help guard against false positive O_2/O_3 signals associated with hydrogen escape, while potentially increasing the probability that biogenic O_2/O_3 will have accumulated to detectable levels. We suggest an integrated observation strategy for fingerprinting oxygenic photosynthetic biospheres on terrestrial planets with the following major steps: (1) planet detection and preliminary characterization; (2) search for O_2/O_3 spectral features with high-resolution spectroscopy; (3) further characterization and elimination of potential false positives; (4) detailed characterization and the search for secondary biosignatures.

Identification of a pigment features associated with oxygenic photosyntheis such as the “red edge” spectral feature would be a particularly strong second biosignature, because it would be consistent with the hypothesis that the O_2 was generated by oxygenic photosynthesis. To further improve confidence in identifying surface signs of photosynthesis, the reflection spectra of the mineral background must also be characterized. Newly developed measurements such as the linear and circular polarization spectra of chiral biomolecules can potentially help rule out mineralogical false positives. In addition, models that predict the surface coverage of a planet’s photosyntheic organisms are needed to better understand the detectability of these signals.

In addition to considerations of “false positives”, some types of biospheres may result in “false negatives”: i.e. biospheres that do not produce remotely detectable biosignatures. These types of planets must be understood and should be considered when selecting the most promising targets for biosignature searches. Earth's atmospheric evolution demonstrates that biogenic gases may remain at undetectable levels despite their production by a surface biosphere (Reinhard et al., 2017; Rugheimer Kaltenegger, 2018.

3 Anticipated Progress in the Astro2020 Era

3.1 Advances in biosignature theory

Much of the top-level theory of biosignatures is described in qualitative terms, and the associated advice to mission/instrument design teams is similarly qualitative. For example, we know that the confirmation of biosignatures requires a comprehensive classification of the planetary environment, which in turn suggests observations with as broad of a wavelength range as possible. But evaluation of detailed trade-offs for specific instruments, and eventually the interpretation of data from biosignature searches, will be best enabled by a more quantitative framework. Fortunately, efforts are underway to produce such frameworks.

Assessing the presence or absence of life on a planet in a quantitative manner is an inherently complex problem, requiring comprehensive analyses of the planetary context. Any planet will have multiple systems that interact with each other, often in nonlinear ways. Accounting for this in a quantified manner – and doing so in a way that is flexible enough to handle alien worlds with potentially alien climates and alien life - requires an encompassing framework. At the EBWWW, a variety of approaches were discussed, including: process-based planet systems[1] models; quantification of thermodynamic and/or kinetic disequilibrium in a planet's atmosphere (after Krissanssen-Totten et al., 2016); assessment of the complexity of atmospheric photochemical networks (after Holme et al. 2011); and utilization of Bayes' Theorem to assess the data from a single planet or a series of planets.

Since the workshop, many groups have applied artificial intelligence and machine learning methods to a number of related problems, and preliminary work using these methods for biosignature detection is now appearing at conferences. Critically, many of these techniques are being developed for *in situ* searches for life in our Solar System. There are fundamental and practical differences between *in situ* searches for life on Mars/ocean worlds and remote searches for life on exoplanets, yet it may be possible to apply similar quantitative techniques such as network analyses or Bayes' theorem. This would provide a new ability to compare and contrast these searches for life.

Progress and future work in conceptualizing and developing these comprehensive modeling tools are reviewed in the EBWWW paper by Walker et al. (2018). The tools for simulating data that could come from inhabited/uninhabited worlds are already under development with both flexible 1-dimensional atmospheric models that can be coupled to subsurface and escape models, and comprehensive but less flexible 3-dimensional global climate models. Current work - by large interdisciplinary teams - is increasing the comprehensiveness of the former models as well as the flexibility of the latter ones. We also must couple/incorporate models of space weather and stellar

[1]By "planet systems" we mean: the study of the interacting systems operating in and on a planet, similar to Earth systems science.

evolution into these atmospheric/surface models. This development of models must continue - and the community involvement in their development must be expanded. We also require advancements in chemistry and biology research on life's origins on Earth, and the environments in which life might originate elsewhere, to help with our assessments of P(life). Finally, we must advance our grasp of the likelihood of certain biological innovations, and better understand the full range of metabolisms life can utilize for obtaining energy, beyond those on modern Earth.

3.2 Advances in Observation: Biosignature Observatories

The most critical step in our search for extrasolar life is to obtain spectra of potentially habitable planets in a variety of stellar contexts. A handful of Earth-sized planets in the HZs of late-type stars have already been identified (Anglada-Escudé et al., 2016; Dittmann et al., 2017; Gillon et al., 2017), including a few that are close enough for follow-up observations. Soon, discoveries of similar targets will be accelerated by TESS (2018-), CHEOPS (2019-), and ongoing/future ground-based RV surveys. Follow-up observations of such targets could be conducted via transit spectroscopy with the James Webb Space Telescope JWST (2021-), Astro2020-era ground-based telescopes (GMT, TMT, E-ELT) and Astro2020-era flagship space telescopes (OST, LUVOIR, HabEx). These will constitute many of the highest-profile exoplanet observations made in the 2020's and beyond.

High-contrast direct imaging of these worlds may be possible through Astro2020 ground-based observatories with second-generation adaptive optics and instruments, and through a HabEx/LUVOIR-like space observatory. The false positive concerns noted above – as well as concerns about habitability – are greatest for planets in orbit around M dwarf stars (Meadows, 2018). Such concerns should not dissuade us from observing M dwarf planets, as the theories and models that gave rise to the concerns must be tested with observations. However, they should be considered when selecting and planning observations, and they highlight the need to eventually conduct observations of planets around Sun-like (F/G/K) stars, where the known mechanisms for generating biosignature false positives are more limited.

The spectroscopic characterization of potentially Earth-like worlds around Sun-like stars demands space-based high-contrast observations. Transit spectroscopy is not capable of the sensitivities required to characterize these targets, and ground-based systems are not expected to achieve the contrast required for direct imaging of them. These observations are not feasible with current and planned space-based facilities. Instead, they require new strategic missions that are explicitly designed for direct imaging of Earth-like planets around Sun-like stars. This is one of the major science goals for the HabEx and LUVOIR concept studies, driving many of their technical requirements. More details on the capabilities of these observatories can be found in other white papers, and in the reports they are preparing for delivery to the Astro2020 panel.

4 Community needs for the search for life on exoplanets

To realize our goals, this field requires the following developments in addition to the observatories required to conduct biosignature searches:

- A more complete incorporation of first-principles biology/ecology into the field and models of fundamental abiotic processes under different planetary conditions
- Evaluation of the wealth of potential new biosignatures, both surface and gaseous, and consideration of their false positives with sustained institutional support to characterize the physical and chemical properties of potential biogenic gases
- An improved capability to predict the expression of photosynthesis in different stellar-planetary environments
- Development and infrastructure support for 3-D general circulation models (GCMs) for exoplanets, to simulate biosignatures in 3-D
- Expansion of 1D planetary model coupling of interior, atmosphere, exosphere, climate, ocean, and biology, and star to simulate biosignatures in different contexts.
- Better accounting of model uncertainties in all the above
- Development of quantification techniques, including (but not limited to) network analyses, retrievals of surface fluxes of potentially biogenic gases, Bayesian frameworks, and measurement of thermodynamic and kinetic disequilibrium.
- The continued growth and strengthening of a diverse, interdisciplinary, and international community of scholars, to ensure the inclusion of the myriad perspectives required to meet the needs and challenges listed above.

The last two items are especially critical. A quantitative approach to biosignatures will advance our field in multiple ways, and will only be possible if it is developed by and for a diverse community of scholars. For exoplanet astrobiologists, a quantitative approach will be a powerful way to consider future mission/instrument trade-offs, and to inform future target selection. It will also yield a quantitative approach will provide a tool to compare possible biosignatures across targets. For our scientific colleagues beyond astrobiology, this approach will provide a rigorous test of our conclusions. And for the general public and to stakeholders, it will lead to the ability to clearly and consistently communicate our level of confidence that we are not alone.

Finally, we must also consider the potential ”We are not alone!” headline moment in the context of the scientific method. The intense, world-wide attention that moment will bring is sure to also bring tremendous skepticism and scrutiny from the global scientific community. It is possible – perhaps even likely – that scrutiny will lead to subsequent publications highlighting a previously unknown (or under-appreciated) non-biological method for producing the signals claimed as signs of life. But that is not a reason to avoid embarking on the search for life among the stars. Instead, we think it is one of the greatest reasons that this search should begin. This moment would highlight something profound: the application of the scientific method to the search for life. That is this community's ambitious – yet attainable – goal.

The exoplanet biosginatures community has developed hypotheses and the models required to make predictions from those hypotheses. What is missing are the data to test those predictions. Such data can be obtained by observatories that we can now build. We ask that you prioritize these observatories, so that our hypotheses may be put to the test. Success in this endeavor through the rigorous application of the scientific method would change the course of human history.

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Solar systems in the midst of their death throes may offer planetary scientists a chance to search for surface life on their far-flung surface moons, says a new paper. The idea is that after sunlike stars go off the hydrogen-burning, so-called main sequence phase of their evolution, their expansion as dying red giants would cause a big thaw in their outer solar systems. Frozen rocky planets as well as icy moons might thaw enough to support liquid water on their surfaces.Â Once exposed, it may interact with the atmosphere and potentially create remotely observable biosignatures, lead author Thea Kozakis, a doctoral student in astronomy at Cornell Universityâ€™s Carl Sagan Institute, told me. Recommended For You. Scientists now think we may be able to detect signs of life on planets beyond our solar system in the next few decades, but to do so new tools and techniques will be required.Â These papers will serve as a reference for future research into how scientists can search for signs of life in the cosmos using telescope observations.Â Formed three years ago, NASA's Nexus for Exoplanet System Science (NExSS) is an international network that brings researchers from a variety of disciplines to understand how we can characterize and eventually search for signs of life, called biosignatures, on exoplanets.Â Mission concepts with biosignature detection as a central driver are being discussed for launch in the 2030s. Life Beyond the Solar System: Remotely Detectable Biosignatures. This white paper reviews the scientific communityâ€™s ability to use data from future telescopes to search for life on exoplanets. It summarizes products from the Exoplanet Biosignatures Workshop Without Walls (EBWWW). This effort led to papers that constituted the Exoplanet Analysis Group's (ExoPAG) 16th Science Assessment Group (SAG 16). Dreier. Casey. The Planetary Society. Thinking Big: How Large Aperture Space Telescopes Can Aid the Search for Life in Our Lifetimes. We discuss the capabilities needed to conduct the most s Life Beyond the Solar System: Remotely Detectable Biosignatures, Astro2020: Decadal Survey on Astronomy and Astrophysics, science white papers, no. 528. 73. Dotson, L, G Barentsen, C Hedges, JL Coughlin. (2019) â€œHundreds More Planets Await Discovery in Kepler's K2 Data Setâ€.Â Solar System Ice Giants: Exoplanets in our Backyard, Astro2020: Decadal Survey on Astronomy and Astrophysics, science white papers, no. 176; BAAS 51, id.176. 196. SÃ¡enz, J.S., Airo, A., Schulze-Makuch, D., Schloter, M., and Vestergard, G. (2019) Functional traits co-occurring with mobile genetic elements in the microbiome of the Atacama Desert. T he search for life beyond the Solar System is a significant motivator for the detection and characterization of extrasolar planets around nearby stars. We are poised at the transition between exoplanet detection and demographic studies and the detailed characterization of exoplanet atmospheres and surfaces.Â Such system-level approaches serve as frameworks and provide foundational concepts for discussions relating to exoplanet biosignatures. 3.1. Observations of Earth.