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An Astrobiology Science Strategy for the Search for Life in the Universe

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SPACE STUDIES BOARD

An Astrobiology Science Strategy for the Search for Life in the Universe

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Authorization Language

National Aeronautics and Space Administration Transition Authorization Act of 2017 (P.L. 115-10), Section 509

SEC. 509. ASTROBIOLOGY STRATEGY.

(a) STRATEGY.—

(1) IN GENERAL.—The Administrator shall enter into an arrangement with the National Academies to develop a science strategy for astrobiology that would outline key scientific questions, identify the most promising research in the field, and indicate the extent to which the mission priorities in existing decadal surveys address the search for life's origin, evolution, distribution, and future in the Universe.

(2) RECOMMENDATIONS.—The strategy shall include recommendations for coordination with international partners.

(b) USE OF THE STRATEGY.—The Administrator shall use the strategy developed under subsection (a) in planning and funding research and other activities and initiatives in the field of Astrobiology.

(c) REPORT TO CONGRESS.—Not later than 18 months after the date of enactment of this Act, the National Academies shall submit to the Administrator and to the appropriate committees of Congress a report containing the strategy developed under subsection (a).

Statement of Task

In preparation for the upcoming decadal surveys and building on NASA's current Astrobiology Strategy 2015, this committee shall:

- Outline key scientific questions and technology challenges related to the search for life;
- Identify the most promising key research goals in the field of the search for signs of life in which progress is likely in the next 20 years;
- Discuss which of the key goals could be addressed by U.S. and international space missions and ground telescopes in operation or in development;
- Discuss how to expand partnerships in furthering the study of life's origin, evolution, distribution, and future;
- Make recommendations for advancing the research, obtaining the measurements, and realizing NASA's goal to search for signs of life in the universe; and
- Consult with the Exoplanet Science Strategy committee.

Collaborative Activities

Given close scientific ties between the astrobiology and exoplanet communities, as well as the parallel study timelines, the SSB and NASA agreed that the **Astrobiology and Exoplanet committees** collaborate. Activities included:

- Chairs and co-chairs communicated and compared approaches;
- A co-chair of the exoplanet committee attended the first meeting of the astrobiology committee;
- A joint session of both committees was held on March 7th, 2018, during the astrobiology committee's second and the exoplanet committee's first meeting;
- Dr. V.S. Meadows served as member of both committees;
- A working group composed of four members of each committee held 3 closed-session teleconferences to exchange ideas and review relevant report elements; and
- SSB staff associated with the studies attended the meetings of both committees.

Report Schedule

Meeting #1*: January 16-18, 2018, Irvine, CA

Meeting #2: March 6-8, 2018, Washington D.C.

Meeting #3: April 25-27, 2018, Washington D.C.

Report delivery to NASA: September 28, 2018

Public release of report: October 10, 2018

**52 White papers originating from members of academia, employees of the federal government, and members of the general public were received and considered.*

Key Take Home Messages

Go Broad: Successful search strategies for life must integrate the idea that no one biomarker is infallible, no single geochemical scenario is the key, life need not be "as we know it." The central theme to the report is the recommendation for "outside the box" thinking in all things pertaining to the search for life.

Go Deep: Flowing from this, and in light of recent exciting discoveries on Earth, Mars, Ocean Worlds and exoplanets, the report recommends a broader perspective that includes subsurface environments as targets for the search for life.

Go High-Contrast: Spectroscopic measurements and high-contrast, near-term space- and ground-based direct imaging missions will, over the next two decades, enable remote characterization of exoplanet atmospheres and the search for potential biosignatures for terrestrial exoplanets orbiting M-dwarf stars—a major theme identified as well in the Exoplanet Science Strategy (2018).

Common Themes

Finding: Given the considerable rate of advancement in astrobiological science since the 2015 NASA Astrobiology Strategy was published, significant strategy updates and new discoveries can be addressed in this report.

Finding: Astrobiology system science is the study of the interactions within and between the physical, chemical, biological, geologic, planetary, and astrophysical systems as they relate to understanding how an environment transforms from non-living to living and how life and its host environment coevolve.

Finding: Cross-divisional collaborations promoted by NASA's Astrobiology Program between Earth science, astronomy, heliophysics, and planetary science have begun the task of breaking down disciplinary entrenchments and are helping the astrobiology and exoplanet communities reach their full potential.

Evolving Thinking on Habitability

Finding: Systems level emergence-of-life research incorporating thermodynamic principles is important for understanding life as a planetary phenomenon.

Finding: Considering the coevolution of early Earth environments in the context of multiple parameters (e.g. T, P, salinity, pH) and over a range of spatial and temporal scales advances the integration of prebiotic chemistry and origins of life research.

Finding: Planetary conditions that may be habitable today or in the past are not necessarily the same as those that could have fostered the emergence of life. Both are important for the search for life.

Finding: Due to the complexity of interactions between physical, chemical, and biological parameters and processes, habitability is not a binary property but a continuum.

Finding: Dynamic habitability and the coevolution of planets and life provides a powerful foundation upon which to integrate diverse astrobiology communities focusing on Earth, the solar system, stellar astronomy, and exoplanetary systems.

Habitability is a continuum defined by multiple evolving parameters

Finding: Comparative planetology between the solar system and exoplanetary systems is a powerful approach to understanding the processes and properties that impact planetary habitability; essential to inform experiments, modelling, and mission planning; and fundamentally requires cross-divisional collaboration between planetary scientists and exoplanet astronomers.

Recommendation: NASA and other relevant agencies should catalyze research focused on emerging systems-level thinking about dynamic habitability and the coevolution of planets and life, with a focus on problems and not disciplines; i.e., by using and expanding successful programmatic mechanisms that foster interdisciplinary and cross-divisional collaboration.

Expand the Search for Life to Subsurface

Finding: Expanded understanding of habitability of chemosynthetic subsurface environments, brine stability, and adaptations of life to saline fluids have widespread implications for the search for life.

Finding: "Slow" life that is barely able to survive in an austere environment may be detectable because the noise level is low, whereas "fast" life in a rich environment may be detectable because the signal is high. Assessing the relative signal-to-noise of each type of population in its environmental context would help identify corresponding biosignatures that are most relevant and distinctive.

Recommendation: NASA's programs and missions should reflect a dedicated focus on research and exploration of subsurface habitability in light of recent advances demonstrating the breadth and diversity of life in Earth's subsurface, the history and nature of subsurface fluids on Mars, and potential habitats for life on Ocean Worlds.

Exploring Habitability of Exoplanets

Finding: The discovery of numerous nearby exoplanets orbiting in their host star's habitable zone coupled with estimates of the fraction of stars with terrestrial-sized, habitable-zone planets has matured the search for evidence of life beyond the solar system enough to warrant taking the next steps toward its discovery.

Finding: The availability of near-term data on the atmospheres of terrestrial exoplanets orbiting M-dwarf stars will enable the first observational tests of their potential habitability.

Finding: Because of the coevolution of host star and exoplanet, stellar activity and evolution are critically important for understanding the dynamic habitability of exoplanets.

Finding: The context of solar and planetary system architecture and evolution is important for determining a planet's history of habitability and limits on habitability, and is important to inform target selection and exploration.

Enabling Technologies and Approaches

Finding: Continued theoretical modeling of planetary environments, including model inter-comparisons, is required to explore processes, interactions, and environmental outcomes and to understand habitability and biosignatures in the context of their environment.

Finding: Techniques based on statistical methods, scaling laws, information theory, and probabilistic approaches are useful in other branches of science and are increasingly being applied in the search for life.

Finding: Technologies for spectroscopic measurements and high-contrast direct imaging have advanced rapidly in the last decade, making possible the remote characterization of the atmospheres of nearby rocky exoplanets and enabling the search for potential biosignatures within the next two decades.

Recommendation: NASA should implement high-contrast starlight suppression technologies in near-term space- and ground-based direct imaging missions.

Systematic Re-Evaluation of Biosignatures

Finding: The catalog of potential biosignatures would benefit from a systematic re-evaluation and increased understanding of the nature and detectability of biosignatures, especially for in situ detection of energy-starved or otherwise sparsely distributed life such as chemoautotrophic and subsurface life.

Finding: Although suggestive of life and worthy of follow-on investigation, thermodynamic disequilibrium may result from a range of abiotic and biological processes and is therefore not always a biosignature.

Recommendation: NASA should direct the community's focus to address important gaps in understanding the breadth, probability, and distinguishing environmental contexts of abiotic phenomena that mimic biosignatures.

Recommendation: The search for life beyond Earth requires more sophisticated frameworks for considering the potential for non-terran life, therefore, NASA should support research on novel and/or agnostic biosignatures.

Frameworks for Assessment of Biosignatures

Finding: Characterizing the atmospheres and incident radiation fluxes for exoplanets of different sizes, compositions, and stellar irradiances is important for confident assessment of planetary habitability and biosignatures because it increases understanding of the physical and chemical processes that lead to false positives and negatives.

Finding: Re-examining controversial biosignatures from Earth's early sedimentary rock record can provide an important test-bed for biosignature assessment frameworks.

Recommendation: NASA should support expanding biosignature research to addressing gaps in understanding biosignature preservation and the breadth of possible false positives and false negative signatures.

Recommendation: NASA should support the community in developing a comprehensive framework for assessment—including the potential for abiosignatures, false positives, and false negatives—to guide testing and evaluation of in situ and remote biosignatures.

Enabling Technologies

Enabling Technologies: Development of mission-ready, life detection technologies and integration of astrobiological expertise in all mission stages—from inception and conceptualization, to planning, development, and operations—are needed.

Recommendation: NASA should accelerate the development and validation in relevant environments, of mission-ready, life detection technologies. In addition, it should integrate astrobiological expertise in all mission stages—from inception and conceptualization, to planning, to development, and to operations.

Private, Interagency and International Partnerships (1)

Finding: The search for life beyond Earth presents attractive opportunities for public, private, and international partnerships.

Finding: Space-based observation of nearby transiting Earth-like planets orbiting M-dwarf stars will be enhanced by complementary data sets acquired by ground-based giant segmented mirror telescopes—e.g., direct imaging, radial velocity measurements, and atmospheric spectra.

Finding: International and philanthropic investment in the search for technosignatures over the last few years have greatly enhanced search capabilities. Corresponding improvements to radio and optical facilities have also benefited the broader scientific community.

Private, Interagency and International Partnerships (2)

Finding: Unified research strategies between relevant entities—including, but not limited to NASA, NSF, and NOAA—for conducting research in shared areas (e.g., polar regions and other difficult-to-access analog environments) and with shared infrastructure (e.g., ground- and space-based telescopes) would facilitate advances in astrobiology.

Finding: The nucleation of government-level astrobiological partnerships that has been initiated by NASA has the potential to precipitate formation of an international organization with a unified focus on solving the immense challenges of detecting and confirming evidence for life within and beyond the solar system.

Recommendation: NASA should actively seek new mechanisms to reduce the barriers to collaboration with private and philanthropic entities, and with international space agencies to achieve its objective of searching for life in the universe.

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Supplementary Slides

New Life Detection Technologies (1)

Finding: Rapid progress in the development of artificial intelligence machine learning algorithms has the potential to improve analysis of the large, complex data sets increasingly common to astrobiology.

Finding: The commercial availability of compact, low-power, RNA and DNA sequencing devices could contribute significantly to the robustness of the current portfolio of life detection technologies.

Finding: Current technology for DNA amplification and sequencing may be useful for in situ detection of terrestrial contamination and lifeforms that are closely related to terran life, but at present, they are not sufficiently agnostic to the subunit composition of an informational heteropolymer.

Finding: New technologies for microscale and nanoscale analyses (e.g. optical microscopy, Raman spectroscopy, laser-induced breakdown spectroscopy, infrared, and others) offer promise for detection of microscale biosignatures.

New Life Detection Technologies (2)

Finding: In situ detection of life is best advanced by integrated suites of instruments or single instruments that permit multiple analytical techniques, including non-destructive approaches, to be applied to the same materials.

Finding: It is important that science requirements drive sample handling technologies—including ingestion and non-destructive sample preparation and analysis—rather than off-the-shelf engineering solutions or ease of implementation.

Finding: Because of possible ambiguity in proposer-defined instrument success criteria, there is inherent risk in using these to propose, evaluate, and select instruments designed to detect biosignatures, rather than using observation and measurement validation standards established by community consensus.

Finding: Instrument evaluation and selection policies favor low technology risk with, in some cases, potentially low scientific payoff which can inhibit development and selection of potentially game-changing life detection technologies.

Finding: Planning, implementation, and operations of planetary exploration missions with astrobiological objectives have tended to be more strongly defined by geological perspectives than by astrobiology-focused strategies.

Recommendation: NASA should accelerate the development and validation in relevant environments, of mission-ready, life detection technologies. In addition, it should integrate astrobiological expertise in all mission stages—from inception and conceptualization, to planning, to development, and to operations.

Definitions

Dynamic Habitability considers that habitability is more appropriately thought of as a continuum—that an environment may transition from inhabitable to habitable over different spatial and temporal scales as a function of planetary and environmental evolution, the presence of life, and the feedbacks between related complex physical, chemical and biological parameters and processes. Life and its environment change together to maintain a habitable Earth. Planetary environments that may be habitable today or in the past are not necessarily the same as those that could have fostered the emergence of life.

Definitions

Agnostic biosignature research explores frameworks and techniques for universal life detection that do not presuppose any particular molecular framework (Cronin and Walker, 2016) or evolutionary endpoint (Cabrol et al., 2016). Agnostic biosignatures are not tied to a particular metabolism informational biopolymer, or other characteristic of life as we know it, but which may manifest as unexpected complexity either in a system-wide alteration of a planetary environment or in preserved molecules.

Examples: - conceptualization of the number of pathways by which a given molecule can be assembled and the probability of its formation in the absence of biology

- elemental and/or isotopic gradients and disequilibrium redox chemistry inconsistent with the abiotic environmental baseline

Definitions

Technosignatures are signs of technologically-advanced life, and are legitimate, if difficult to constrain, biosignatures for astrobiological searches. Examples include leakage from communication signals, or signals intentionally beamed to Earth. The search for technosignatures is a high risk, high reward approach to the search for life, and its probability of success is poorly understood.

Finding: International and philanthropic investment in the search for technosignatures over the last few years have greatly enhanced search capabilities. Corresponding improvements to radio and optical facilities have also benefited the broader scientific community.