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Decadal Survey on Biological and Physical Sciences Research in Space 2023-2032

Topical:

Co-leveraging scientific advances in Space Biology and Astrobiology towards achieving NASA's life science objectives

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Executive Summary:
Distinct lines of scientific inquiry drives the separation of NASA's fundamental life science research into Space Biology and Astrobiology. This division developed as a way to place life scientists alongside experts in the physical constraints that define the acclimation, adaptation and evolution of biology systems relevant to their respective subjects. For astrobiology, integration with disciplines such as geology, geochemistry, astronomy, planetary science, etc., enables a comprehensive assessment of the physical environment and its co-evolution with biological processes. Space Biology's co-location with Physical Sciences places life science researchers adjacent to experts in the physical phenomena associated with microgravity and spaceflight, enabling an understanding of how the spaceflight environment affects biological systems.

Despite this separation, aspects of both disciplines have converged on a similar, fundamental objective: to describe and understand the dynamics of complex living communities in the contexts of their physical environments. While the environmental systems and timescales are dramatically different, continuing to motivate the separation into distinct fields, similarities in the underlying objective present opportunities to find efficiencies, reduce overlap, and minimize duplication of effort. Space Biology and Astrobiology share a common need to understand microbial physiology in extreme environments – whether the 'built' spaceflight environment or the natural environments in which many astrobiology studies are conducted. In particular, open questions in each discipline require the development of quantitative frameworks, applicable at the *ecosystem* level, that support predictive capabilities for environments where observations are sparse.

Additionally, both disciplines have a need to prepare, detect, and analyze the (potential) biological signal in complex samples-often in a completely autonomous fashion. The next decade will see NASA Space Biology moving to understand and describe the effects of the beyond low-earth orbit (BLEO) spaceflight environment on living systems. This new direction will dramatically reduce the opportunities for ground-based analysis of space-flown samples, driving space biology investigations towards fully autonomous experiments and missions. At the same time, astrobiology life detection missions aimed at detecting biosignatures on Mars and icy moons in the outer solar system could benefit from fully automated sample processing and analysis. There are opportunities to leverage instrument and method development between both disciplines within the context of these BLEO missions.

We present the following recommendations to the Decadal Survey Committee for consideration:

1) NASA's Biological and Physical Sciences and Planetary Sciences Divisions should cooperate on the joint development of ***data analysis tools*** to characterize their respective ecosystems, with an emphasis on computational and experimental systems biology approaches.
2) They should leverage ***life science technology development*** relevant to both disciplines.
3) Space Biology BLEO efforts should leverage the existing knowledge in the Planetary Sciences Division for ***planning and executing deep space autonomous science*** missions.
4) Space Biology should include ***secondary payloads on PSD missions*** to the outer solar system to increase BLEO flight opportunities.
5) Astrobiology should ***leverage the Space Biology biospecimen sharing infrastructure*** to increase the science yield of their investigations.

Space Biology: moving beyond low Earth orbit

Characterizing the effect of the beyond low Earth orbit (BLEO) space environment on biological systems is critical to support human space exploration to the Moon and then to Mars. The next decade of Space Biology research will need to focus on this poorly characterized, multivariate stress environment to ensure crew and mission safety. A confounding factor as we move to BLEO is infrequent access to the BLEO space environment coupled with an infrequent/inconsistent crew time dedicated to science on lunar missions. Thus, Space Biology will be challenged to characterize the effects of complex physical environments on living systems via largely autonomous experimental design. NASA's Planetary Science Division, co-located with Biological and Physical Sciences within the Science Mission Directorate, has experience in highly autonomous operations that can be leveraged to bridge these challenges.

Co-evolution of life and its adjacent environment

The observed phenotype for complex ecosystems is an interplay between its internal biological capabilities and the dynamics of the external environment. Much of NASA's life science objectives require a mechanistic understanding of these two components: what are the underlying capabilities of organisms in a given environment, how does the environment constrain that biology, and how do these "co-evolve" over time? Currently, NASA clusters its life sciences based on the external environment. Space Biology is co-organized with the Physical Sciences, placing life science researchers adjacent to experts in the physical processes of microgravity, enabling an understanding of how the spaceflight environment may affect biological systems. Astrobiology is integrated with disciplines such as geology, geochemistry, astronomy, planetary science, etc., enabling a comprehensive assessment of the physical environment and its co-evolution with biological processes. Still, while the overarching science goals differ, these areas share the need to describe the interface of an ecosystem with its external constraints.

Joint Method Development: addressing environmental constraints on living systems

> **Recommendation:** NASA's Biological and Physical Sciences and Planetary Sciences Divisions should cooperate on the joint development of ***data analysis tools*** to characterize their respective ecosystems, with an emphasis on computational and experimental systems biology approaches.

An area consistent between Space Biology and Astrobiology are ecosystems where the physical environment applies the dominant, external constraint. Environmental parameters are experimentally accessible and their effects on a biological system can be structured into hypothesis-driven investigations. Astrobiology and Space Biology share a common need to understand microbial physiology in extreme environments – whether that be the 'built' spaceflight environment on a mission to Mars, or the natural environments in which many astrobiology studies are conducted.

Systems Biology has been a focus area of NASA's Space Biology program since it was specifically called out in the 2010 CBPSS Decadal Survey. The subsequent decade saw a dramatic uptick in using 'omics data to study biological systems in the spaceflight environment. However, to date these efforts have largely resulted in an incomplete, and at times conflicting, understanding of the biological response to spaceflight. One hypothesis for this challenge is that spaceflight stressors are subtle, roughly equivalent, and interacting. As a result, observational studies of the microbial ecosystem do not have the power to extract a mechanistic understanding of the biological response. This is compounded by the lack of access to the microgravity environment and imperfect ground analogs. Addressing this challenge requires a suite of tools, scalable to the ecosystem level, that can derive mechanistic relationships between the environment and the biological phenotype.

NASA's Space Biology efforts need to extend beyond 'omics analysis into computational modeling of the effects of space flight stressors on biological systems. Computational systems biology, as an effort to develop mathematical frameworks representing systems of interest, takes a step beyond 'omics. These frameworks create a powerful interpretive context for 'omics datasets by couching them within a series of interconnected networks that represent the biological (eco)system at a mechanistic level.

A barrier to method development on Space Biology ecosystems, such as the spacecraft built environment, is that we have yet to determine the relative contribution of the multiple factors (water and nutrient availability, chronic low-dose radiation, a lack of buoyancy-driven convection, and other stressors) on microbial ecosystem dynamics. Because some of these factors are novel environmental conditions to which Earth biology has not been exposed during evolution, it is difficult to develop and validate a systems biology method in such an environment from scratch. Astrobiology analog environments also typically evaluate a number of dominant environmental constraints on the extant biology (e.g., temperature, resource availability, pH, salinity, etc.), some of which overlap with spaceflight environmental conditions. Thus, collaboration between Astrobiology and Space Biology on tractable analog studies offer a way to mature systems biology methods towards open questions across the NASA life sciences, in both conceptual and methodological terms, while also leading to improved models and predictive capabilities.

Recommendation: NASA's Biological and Physical Sciences and Planetary Sciences Divisions should cooperate on leveraged development of ***life science technology*** relevant to both disciplines.

Autonomous Biological Payloads: an opportunity for leveraged technology development

Small biological payloads and free-flyers (e.g., CubeSats) have been successfully employed to probe relevant Astrobiology and Space Biology science questions, to include paving the way to BLEO investigations. As the current plans for manned lunar exploration does not include a persistent presence on the lunar surface or on the Gateway platform, there is a need to increase the complexity of the biological questions that can be addressed via automated platforms. This will require advances in technology, method, and data analysis (please see the Campaign White Paper: "*Advancing telemetry-based biology for the Artemis era and beyond*").

Over the past two decades, NASA has developed, space qualified, and operated a range of bioanalytical/bioprocessor systems that comprised the payloads of multiple nanosatellite missions to study living organisms in Earth orbit (e.g., Ehrenfreund et al. 2014; Woellert et al. 2011; Ricco et al. 2011; Ricco et al. 2007). While these missions had objectives focused on the health and function of Earth life, many of the technical functions they performed will also be needed for in-situ autonomous life detection during Astrobiology missions. Additional opportunities to leverage the nanosatellite developments include stringent sterility and cleanliness requirements as well as the general microfluidic design, development, fabrication, integration, sterilization, and test approaches that are applicable to meeting planetary protection requirements. In one relevant example, the O/OREOS (Organism/Organic Exposure to Orbital Stress) nanosatellite included a life science experiment that required perfect sterility: a measurement would fail if a single viable bacterium or fungal spore were present in any of half a dozen nutrient-filled fluidic compartments integrated with and isolated by actively controlled valves from multiple microwells containing dried bacterial spores. Results from Earth orbit (Nicholson et al. 2011) across 6 months showed that perfect sterility was indeed maintained in all three experiments, the last of which was operated 11 months after loading the isolated bacteria and reagents in our facilities; the same stringent sterility was maintained in the three experiments of the matching ground-control system as well.

Currently, many of the technical functions of these nanosatellite bioanalytical/bioprocessor payloads are being advanced and implemented as part of search-for-life technology development projects funded under the NASA SMD Concepts for Ocean worlds Life Detection Technology (COLDTech) and Instrument Concepts for Europa Exploration-2 (ICEE-2) programs (e.g., Brinckerhoff et al. 2019; Quinn et al. 2019; Radosevich et al. 2019). These functions include: integrated pumping, metering, valving, and control of flow rate and pressure: quantitatively transferring the sample from the collector; filtering non-soluble particles by size (for separate analysis); in-situ measurement and adjustment, up or down, of both ionic strength (conductivity) and pH; admixture of reagents such as dyes, stains, and fluorescent labels; evaporative concentration; degassing and trapping of bubbles; distributing appropriately preprocessed sample aliquots to each of the analytical instruments at the appropriate flow rate and total fluid volume, with repeat aliquots for redundant analyses that will increase the statistical power of the results. The advancement of these technologies (initially developed for Space Biology) for Astrobiology life-detection missions can in turn feedback to future Space Biology missions to further advance life-science experimental capabilities while simultaneously reducing mission risk.

Autonomous Biological Payloads: leveraging best practices from PSD missions

Recommendation: Space Biology BLEO efforts should leverage the existing knowledge in the PSD for ***planning and executing deep space autonomous science*** missions.

As Space Biology extends into more complex, autonomous science missions, BPS should leverage the extensive mission experience in PSD. Existing Space Biology autonomous missions have largely been, with the exception of BION, small, single investigator, single experiment payloads. The concept of operations, dealing with distance and data bandwidth issues, complex autonomous data collection, sample preparation, and analysis are complicated when operating BLEO. Applying best practices from PSD to these new biological payloads builds on existing knowledge to increase mission success.

Recommendation: Space Biology should include ***secondary payloads on PSD missions*** to the outer solar system to increase BLEO flight opportunities.

Access to BLEO is highly constrained. To help alleviate this challenge, Space Biology should strive to fund secondary payloads on all missions BLEO, to include PSD missions to the outer solar system. An upcoming opportunity is the Mars Sample Return mission. Placing a biological payload on the sample return craft is a chance to expose biological payloads to a Mars transit mission, informing our understanding of the BLEO environment for future crewed missions to include quantifying the bactericidal conditions of deep space for planetary protection assessments.

Biospecimen sharing and open science: leveraging advances in NASA Space Biology

Recommendation: Astrobiology should ***leverage the Space Biology biospecimen sharing infrastructure*** to increase the science yield of their investigations.

Space Biology has a robust infrastructure to support open science for both data analysis and biospecimen sharing. This service to the broader scientific community continues to yield novel discoveries years after the initial investigation, taking advantage of new technologies and scientific understanding. Leveraging this existing infrastructure for Astrobiology samples has the potential to yield similar benefits. Biological samples from analog sites represent critical resources to the broader Astrobiology community. The lack of a centralized repository prohibits iterative, longitudinal investigations into these ecosystems.

The existing Space Biology infrastructure could be leveraged in several ways. First, leverage the NASA Biological Institutional Scientific Collection (NBISC) tissue distribution process to house and redistribute biospecimens from Astrobiology analog sites. The primary samples from these sites are distinct from sub-cultures and isolates generated post-sampling. Thus, they are similar to biological tissues from flight experiments. Currently, flight tissue requests are vetted via a science review board to ensure the distribution of these limited samples are being used to generate important science relevant to open Space Biology questions. A similar process can be applied to primary samples from Astrobiology analog sites. Additionally, PSD and BPS should collaborate in the Space Microbial Culture Collection at NASA. This institutional scientific collection could house, maintain, and redistribute cultures of microbial isolates from Space Biology, Planetary Protection, and Astrobiology samples.

Summary

While Space Biology and Astrobiology are distinct disciplines, consideration of their respective trajectories in the next decade identifies both areas of common need and opportunities for leveraging. Collaboration in the development of life science technology, data analysis tools, and systems biology approaches can support areas of common need, while leveraging opportunities exist in the areas of autonomous mission concept of operations, access to BLEO through secondary payload opportunities, and sample sharing infrastructure. The co-location of BPSD and PSD within the Science Mission Directorate offers new opportunities to enable such collaboration.

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