# THE BIOLOGICAL AND PHYSICAL SCIENCES IN SPACE DECADAL SURVEY

Statement of

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Chairman Babin, Ranking Member Sorensen, and distinguished members of the Subcommittee thank you very much for the opportunity to speak to you today. My name is Rob Ferl, and I am a Distinguished Professor and Assistant Vice President for Research at the University of Florida, and Co-Chair along with Krystyn Van Vliet of Cornell University, of the National Academies of Sciences, Engineering and Medicine's Decadal Survey in the Biological and Physical Sciences in Space.

Today's speakers focus on how we will operate in space beyond the International Space Station (ISS). I am here to address what we should do in space on and beyond the ISS, and why it is essential for the United States. These concepts of the "what" and the "why" were the very purpose of the biological and physical sciences (BPS) in space decadal survey, a congressionally mandated study recently completed and delivered to NASA, Congress, and the White House. The report describes the value of this field and its role in American leadership in space and establishes priorities for the next decade. BPS science, conducted since the first US space missions, deals with the fundamental principles that govern the effects of spaceflight on biological and physical systems – how, for example, fluid flows in space compared to terrestrial gravity affects human biology down to the cellular level and the transfer of cryogenic fuels on the systems level. So many of the physical forces that shape our understanding of the world on Earth simply do not apply directly in space. BPS science guides the development of understanding, leading to the engineered vehicles that support life and exploration in space.

Our report, *Thriving in Space – Ensuring the Future of Biological and Physical Sciences Research, a Decadal Survey for 2023-2032*, was released in September 2023. It is only the second decadal survey in this field, and the first one produced since NASA moved biological and physical sciences into the Science Mission Directorate. It results from the work of over sixty volunteers from academia, government, and industry, working over two years, holding data gathering sessions, and soliciting inputs from the scientific community, including over 350 input papers.

The title of our survey, *Thriving in Space*, is an intentional description of the body of work. Over the past 50 years we have talked about going to space. Now we are talking about living and working and staying in space, and soon on the Moon, and Mars. *Thriving in Space* captures that bold transition from tentative sojourning, to establishing permanent presence. Indeed, over the past decades we have gone from occasional space sorties to a continuous occupation of space. The United States has had astronauts on orbit continuously since November 2, 2000, when Expedition 1 arrived at the International Space Station. The number of people in space, and the number of companies moving their processing into space, has risen to the point where the ISS is at maximum capacity, and yet the demand continues to increase.

This increase in demand and interest in space both requires and is enabled by the science that underpins our ability to live and work and discover in space.

**The Space Science Decadal Surveys**

The space science decadal surveys have been essential for our nation, NASA, and their respective scientific communities, and are admired and emulated worldwide. They establish the priorities within our disciplines and have been vital in assuring American leadership in the space sciences. Numerous well-known scientific missions, such as the Hubble Space Telescope, the Parker Solar Probe, and the Perseverance Mars rover, have resulted from the prioritization process established in decadal surveys over many years. Unlike the other space sciences, the biological and physical sciences do not have large, distinct missions like telescopes or planetary rovers. Instead, they comprise hundreds of experiments conducted in areas such as growing plants for food and oxygen generation, studying materials behavior in the space environment, and conducting fluids and combustion research. One of the significant new developments in our study was the recommendation to create focused research campaigns consisting of related experiments and hardware intended to make substantial advances in specific areas to benefit the American space program and the nation at large.

**Biological and Physical Sciences in Space**

Our decadal survey has prioritized the science in this field to provide a basis for the United States' expanding presence in space. This includes finding new ways to feed and support astronauts in Earth orbit, on the surface of the Moon, and eventually Mars. It also contains research on new materials, processes, and manufacturing that can enable astronauts to survive longer and accomplish more during their missions. There has been an American astronaut in orbit every single day for over two decades now, but to sustain that presence and to fully reap the benefits of hundreds of billions of dollars already invested, we need to develop focused research campaigns that can provide the basis for going from merely visiting space to thriving in space. This will be challenging as the International Space Station is retired and we begin transitioning to commercial low Earth orbit platforms and returning Americans to the Moon. The difficulty arises from the critical need for this body of science to feed both the LEO ecosystem development *and* the exploration of deep space.

BPS is the science that seeks an understanding of the unique forces that spaceflight imposes on biological and physical systems. Fluid flow in space, for example, is governed by dramatically different forces than when gravity dominates on Earth. Flames are different when gravity is no longer driving convection. Biological systems, which are largely fluids, must adapt to an environment for which there is no evolutionary preparedness. BPS enables the engineering needed to create our space vehicles and to live inside them. BPS feeds the fundamental science that allows the Human Research Program at NASA to understand the clinical effects on humans in space.

As we open deep space exploration and expand LEO presence for development, there can be no gaps in the ability of BPS science to continue. We cannot, for example, trade a few experiments on the Artemis vehicles for the thousands of experiments that are conducted on the ISS. There must be a smooth transition from ISS to commercial station so as to fully inform Artemis while also driving LEO development.

Our BPS decadal survey prioritized the research in the field over the next decade by establishing eleven key scientific questions to be answered—a substantial reduction and refocusing from the dozens of questions in the 2012 decadal survey. Our report also recommends that some of these questions be retired after they have been substantively answered; in other words, the science research should not be continued if the return on investment diminishes, enabling funds to be directed to more productive areas. The BPS field is not a sandbox for scientists to play in; the goal is to produce benefits for the space program.

For the first time, the biological and physical sciences in space decadal survey also included research campaigns, a series of focused experiments intended to serve a defined goal. Research campaigns, in some cases, will require new hardware. We conducted a technical risk and cost evaluation process to gauge the scope of these campaigns. However, substantial unknowns exist in how these campaigns can be performed, meaning that any cost estimates have enormous ranges. What we do know is that these activities are not inexpensive, and we caution that the total costs of conducting current BPS activities in space are higher than the small BPS budget reflects because of all the things associated with supporting astronauts during their time in orbit. That difference will have to be taken into account once we transition to a more commercial approach where the costs will no longer be subsumed into the NASA ISS operations budget.

**Key Science Questions**
Our report's eleven key scientific questions span three significant research themes in and about the space environment. The three themes are:

*Adapting to Space* Life in space operates differently than life on Earth. It is critical to understand how the space environment impacts human beings as well as the plants and microbes that will be part of future habitat systems.

*Living and Traveling in Space* Human exploration of the Moon and Mars will require longer-duration space missions. For these missions to be successful, it is essential to understand how biological and hardware systems interact over the years and how to derive resources to explore new places sustainably.

*Probing Phenomena Hidden by Gravity or Terrestrial Limitations* Fundamental processes that are not observable on the Earth can be readily seen in spaceflight when gravity is removed from the equation. Space-based laboratories provide the opportunity for significant scientific gains.

**Research Campaigns**
Our report recommended two research campaigns for the future, which we named BLiSS and MATRICES.

*BLiSS* The Bioregenerative Life Support Systems (BLiSS) campaign is targeted to build and understand the systems that would provide high-quality food, refresh air and water, process wastes, and enable the creation of space environments sustainable for long periods of time independent of Earth. BLiSS would enable understanding of the multiple biological phenomena at play while providing a distinct technology gain for space exploration and presenting high return-on-investment for development of sustainable technologies for Earth.

*MATRICES* The Manufacturing Materials and Processes for Sustainability in Space (MATRICES) campaign addresses two challenges in the journey and destination of space travel and habitation: the limited mass of resources launched from Earth for long journeys and limited knowledge of how to repeatably use resources from both the Earth and space to manufacture and repair the world around us, with minimal impact to that world. This campaign envisions the types of materials science, complex fluid dynamics, and manufacturing, near and far from equilibrium conditions, that will be enabled over the next decade in an expected ecosystem that includes ISS, commercial space destinations in low Earth orbit, and planetary space experimental platforms.

In addition to the two research campaigns, the decadal survey included a multi-agency opportunity and one research infrastructure concept. Probing the Fabric of Space-Time (PFaST) is envisioned as a campaign-style, multi-agency opportunity centered on deploying an advanced quantum sensing network. This extremely large-scale research and technology effort scales well beyond the sole domain of NASA. The committee recommended that this opportunity be actively pursued, but only as a multi-agency effort where non-NASA sources provide a substantial majority of the funding. In addition, Polar Radiation of Model Organisms (PRoMO) is a notional concept of future research infrastructure that describes an opportunity for using a space vehicle not currently available to science that underpins the health-risk-based decision process inherent in exploration beyond low Earth orbit. This concept could enable crewless research investigations of physical systems and organisms, including mammals, for extended exposure durations of interest to several key scientific questions.

**Funding, Competition, and Benefits of Discovery**
This will cost more money. The BPS is a little over one percent of the Science Mission Directorate's budget and a tiny fraction of the NASA budget. But the science has been underfunded for many years, resulting in instability and inability to focus on useful goals. If the United States wants to maintain its leadership role for the next generation of space science and exploration, funding for BPS research will have to increase tenfold before the end of the decade. This level of funding is necessary to support a robust and resilient program that can meet the nation's needs and keep it at the forefront of space science. Currently, China has a space station in orbit and is conducting the same kinds of research that Americans have led for decades. Indeed, we are now seeing them perform similar experiments to those we conduct on the ISS. Nobody doubts their resolve to catch up with us and surpass us.

The science of living and working in space both enables space exploration and richly informs life on Earth. It feeds the national need to lead in the development of LEO for both science and development, and deep space for sustained human presence for discovery. Without an ever-increasing understanding of the phenomena and principles that guide both physics and biology in space, we risk the success of our exploration of space. We risk our national goal of leadership in space. With increasing the base of fundamental science understanding of space, we ensure a reliable, sustainable and effective exploration of space and national leadership in space.

Conducting science in space uniquely expands our understanding of the natural universe, and directly translates to applications on the Earth. This is not just the simple derivation of technological spin-offs. In fact, spin-offs are very much a secondary justification. Yes, we will learn about 3D printing organs on the ISS to better inform human health on Earth. However, the deeper value of this science is expanding boundaries and understanding and making new discoveries that *inform how we do other things*. The ISS has produced the coldest place in the universe in order to study the fundamental properties of matter. To explore space and do science in space is to gain fundamental knowledge about the way the universe works and how life on Earth succeeds. The science questions we prioritized for this decade are key to enabling space exploration, cooperation, and competition on the way to the moon and Mars — and key to discoveries and benefits on Earth that none of us can imagine today.

The Key Scientific Questions and recommendations in *Thriving in Space – Ensuring the Future of Biological and Physical Sciences Research, a Decadal Survey for 2023-2032*

**TABLE F-1** Key Scientific Questions for BPS Space Research over the Decade 2023–2032

| Themes | Key Scientific Questions |
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| Adapting to Space<br><br>(Chapter 4) | • How does the space environment influence biological mechanisms required for organisms to survive the transitions to and from space, and thrive while off Earth?<br>• How do genetic diversity and life history influence physiological adaptation to the space environment?<br>• How does the space environment alter interactions between organisms? |
| Living and Traveling in Space<br><br>(Chapter 4) | • What are the important multi-generational effects of the space environment on growth, development, and reproduction?<br>• What principles guide the integration of biological and abiotic systems to create sustainable and functional extraterrestrial habitats?<br>•What principles enable identification, extraction, processing, and use of materials found in extraterrestrial environments to enable long-term, sustained human and robotic space exploration?<br>•What are the relevant chemical and physical properties and phenomena that govern the behavior of fluids in space environments? |
| Probing Phenomena Hidden by Gravity or Terrestrial Limitations<br><br>(Chapter 5) | • What are the mechanisms by which organisms sense and respond to physical properties of surroundings, and to applied mechanical forces including gravitational force?<br>•What are the fundamental principles that organize the structure and functionality of materials, including but not limited to soft and active matter?<br>•What are the fundamental laws that govern the behavior of systems that are far from equilibrium?<br>• What new physics, including particle physics, general relativity, and quantum mechanics, can be discovered with experiments that can only be carried out in space? |

**TABLE F-2** Recommendations for BPS Space Research over the Decade 2023–2032

| Chapter | Recommendation |
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| Framework for Thriving in Space<br><br>(Chapter 3) | Recommendation 3-1: NASA should direct its research resources toward the Key Scientific Questions identified in this study (Table S-1 and Chapters 4 and 5).<br><br>Recommendation 3-2: NASA should work with other U.S. government agencies and other nations' space agencies to coordinate research resources toward the Key Scientific Questions, as relevant to multiple agency missions. |

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| | Recommendation 3-3: As activity in LEO increases, and lunar and Martian missions are increasingly likely, NASA should increase resources dedicated to understanding the answers to these Key Scientific Questions. |
| Science to Enable Space Exploration<br><br>(Chapter 4) | Recommendation 4-1: NASA should continue to strengthen the science exchange between the Biological and Physical Sciences Program and the Human Research Program. Such effort may include establishing a coordinating body and shared research initiatives as well as the two-way exchange of technologies, data, mission science, specimen banking, and plans.<br><br>Recommendation 4-2: NASA should increase resources dedicated to producing and understanding the answers to the Key Scientific Questions that address the transitions to and from space. The committee sees potential for significant advances in space exploration if a biological and physical sciences portfolio in the coming decade is aimed at understanding:<br>• the biological responses that occur during transitions between the Earth and space environments over extended duration and distance to fundamentally enable space exploration.<br>• genetic diversity to understand positive and negative responses and long-term adaptations to spaceflight to accelerate the identification of risks, mechanisms of adaptation, and potential positive adaptations that could improve life in space.<br>• how cells, systems and organisms concurrently adapt to the spaceflight environment and develop mechanisms for encouraging positive and countering negative communicated responses.<br><br>Recommendation 4-3: To ensure the long-term survival of life in the spaceflight environment, NASA should ramp up investigations into space impacts on sustained human presence in space by investigating:<br>• reproduction, development, and evolution within all relevant biological systems.<br>• the relationships between biology and space hardware to ensure structural integrity, optimize recycling, and utilization of local resources.<br>• effective chemical, physical and biological methods for locating, extracting and processing local resources, especially from the Moon, for use in local habitation and downstream production.<br>• fluid physics, combustion, and related sciences to enable sustainable space exploration and habitation. |
| Science Enabled by the Space Environment<br><br>(Chapter 5) | Recommendation 5-1: NASA should substantially increase resources dedicated to producing and understanding the answers to the key scientific questions detailed in this report. This investment recognizes the potential for significant societal impacts utilizing the space environment for the biological and physical sciences portfolio in the coming decade, aimed at:<br>• identifying the mechanisms by which organisms sense and respond to the surrounding environment, including gravitational force.<br>• advancing knowledge of material structure, self-assembly, and stability of materials, including but not limited to soft/active matter, in space |

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| | environments, cognizant of but distinct from the applications of that knowledge to space exploration and habitation (e.g., manufacturing in space).<br>• supporting ground-based and microgravity research on understanding the fundamental laws of systems far from equilibrium especially those that underlie the existence of life.<br>• identifying new principles of physics that can only be discovered through experiments in space, including those governing particle physics, general relativity, and quantum mechanics.<br><br>Recommendation 5-2: For fundamental physics in space, NASA should facilitate durable formation of collaborations and efficient knowledge transfer between researchers working in multidisciplinary teams. This scope to address these multidecadal key scientific questions should include ground-based infrastructure, theoretical and experimental physics, precision measurement and technology development with private sector participants, and coordinated with missions in which BPS research is one among several whole-of-government objectives. |
| | Recommendation 5-3: In all the space-enabled research areas, NASA should allocate funding with an anticipation that new directions of research may arise. |
| Research Campaigns<br><br>(Chapter 6) | Recommendation 6-1: NASA should pursue dedicated Research Campaigns that, through the coming decade, will drive resolution to specific groups of Key Scientific Questions. Coordination beyond NASA, including other federal agencies and the private sector as well as public-private partnerships, should be considered for the dedicated new funding and materials to support these Research Campaigns.<br><br>• BLiSS (Bioregenerative Life Support Systems) to build and understand the systems that would provide high-quality food, refresh air and water, process wastes and enable the creation of space environments sustainable for long periods of time independent of Earth.<br>• MATRICES (Manufacturing mATeRIals and proCEsses for Sustainability in Space) to understand and harness the physical processes by which materials and complex fluids can be repeatably utilized in space, to enable sustainable exploration and circular lifecycles for the built environment on Earth and in space.<br><br>Recommendation 6-2: NASA should pursue development of the Probing the FAbric of Space Time (PFAST) initiative in this decade only if it can obtain substantial (greater than 75 percent) funding from external (i.e., other than NASA) sources. |
| Strategy and Challenges<br><br>(Chapter 7) | Recommendation 7-1: Because the nation benefits from global leadership in space science and technology, and given the emergence of commercial platforms that can be tasked to the nation's science, NASA should:<br><br>• Seek significant funding increases for BPS with new monies or through rebalancing the portfolio across SMD, and in coordination with other U.S. government agencies, as the community needs to grow significantly in size to reach the science goals of the nation; |

- Actively engage commercial spaceflight firms, using science funding as a driver and with all due haste, to ensure that science needs are met with clear priority, guaranteeing that national science needs are enabled along with those of potential commercial customers using those platforms; and
- Ensure that the funded science community fully engages diversity and inclusivity in the pursuit of the nation's space exploration science priorities.

Recommendation 7-2: To maintain research campaign momentum, NASA should require external advisory committees to evaluate Research Campaign team progress and emergent technologies annually.

Recommendation 7-3: Because key questions identified in this study benefit from access to multiple spaceflight related platforms, the Biological and Physical Sciences Program should:

- Coordinate funding opportunities with Space Technology Mission Directorate such that access to the range of spaceflight and spaceflight related platforms is efficiently employed to answer key science questions, especially those questions that inform technology development for space exploration; and
- Maintain a foundational approach to science, building through a strong, vibrant program of ground-based, suborbital, orbital, lunar, Martian, and beyond missions.

Recommendation 7-4: Because Key Scientific Questions identified in this study support the effective utilization of, and benefit from access to, deep space exploration platforms, NASA should ensure that scientific opportunities are maximized within the range of spaceflight and spaceflight related platforms intended for lunar, cislunar and Mars transit solutions.

Recommendation 7-5: The U.S. government, including NASA, should develop and maintain sufficient ground-based infrastructure to validate and support biological and physical sciences missions. Some of these facilities already exist and simply need to be upgraded, while others have yet to be conceived and built.

Recommendation 7-6: NASA should continue and expand the investment in open and shared computational infrastructure (CI) to support storage, analysis and dissemination of its biological and physical data, while ensuring linkage to the original and archived samples.

- For biological sciences, GeneLab should be continued and efforts made t o ensure findable, accessible, interoperable, and reusable (FAIR) access from other critical international biological resource CIs.
- NASA should recognize the need for long-term investment to maintain, update and improve such community-serving CI and physical repositories over time.

Recommendation 7-7: NASA should work with the other appropriate U.S. government agencies with a goal to establish an office or mechanism for commercial sponsorship and collaboration with non-profit organizations including academia and government research agencies. That office/mechanism should have the primary focus of

- coordinating the work between these commercial sectors and government agencies;
- providing guidance on or facilitating research compliance, data security, and material transfer agreements (MTAs), including prototype agreements;
- representing multiple space environments and destinations (for example, not only ISS in low Earth orbit); and
- communicating these opportunities to the research community.

Recommendation 7-8: NASA should work with appropriate government agencies to establish clear guidelines for international collaborations within BPS, in particular, for support of non-U.S. students and scholars, to balance two goals:

- sustain and advance the U.S. leadership in the relevant areas of research, possibly by attracting the best and brightest globally; and
- support a robust global research community and information exchange, fostering partnerships with other space programs and U.S. access to other nations' ground-based and space assets.

Recommendation 7-9: To retire many of the key scientific questions by the end of the decade, NASA should establish support for the Biological and Physical Sciences Program to levels that reflect the current national need and to build the science community in size, diversity of technical expertise and lived experience, and capability to reach the science goals of the nation, toward levels that are an order of magnitude above the current funding and well before the end of the decade.

Recommendation 7-10: To maintain a viable scientific community, the numerical majority of supported principal investigators (i.e., fraction of research team leaders) should be extramural (i.e., not NASA employees) and funding levels should be commensurate with addressing the key scientific questions.

Recommendation 7-11: NASA should establish periodic reviews of selected Research Campaigns to ensure coordinated access to the space environment, publicly communicated progress on research milestones, and facilitation of collaborations and public-private partnerships as required to meet these ambitious goals.

Recommendation 7-12: NASA should identify mechanisms to compete new or additional research campaigns within 5 years, in light of anticipated changes to access to low Earth orbit and the inevitable but unknown changes in research, technology, funding, and space mission directives that will ensue after this report is issued.

Recommendation 7-13: NASA should ensure diversity, equity, inclusivity, and accessibility in the pursuit of the nation's space exploration science priorities, including instituting a requirement of documented progress in diversity among

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| | NASA-sponsored research teams seeking multi-year funding or multiple sponsorship requests over the coming decade. This inclusivity should be intentionally broad in concept, with respect to visible and less visible characteristics of historically underrepresented groups in BPS research and leadership.<br><br>Recommendation 7-14: Project grants should be funded at levels and duration consistent with the project aims with full support for trainees (postdocs, graduate students, and undergraduates), including travel for trainees and principal investigators to support the mission and participate in scientific meetings. Full funding representing the total costs of research (direct and indirect) is imperative to be inclusive of participation by all trainees. |