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Paper Session II-B - Strategies for Conducting Life Science Experiments Beyond Low Earth Orbit

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Strategies for Conducting Life Science Experiments Beyond Low Earth Orbit

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Human exploration beyond low Earth orbit will require terrestrial life to survive and ultimately flourish in environments fundamentally different to those in which it has evolved. The effects of deep space and conditions on the surface of other planets must be studied to understand and reduce the risks to explorers, provide bioregenerative life support, and make full use of the broad research opportunities and scientific benefits offered by such unique environments. Though much is already known about biological adaptations to the space environment, key changes in terrestrial life may only be revealed over complete life cycles and across multiple generations living beyond Earth. The demands and potential risks of exploring and inhabiting other worlds necessitate a detailed understanding of these changes at all levels of biological organization, from genetic alterations to impacts on critical elements of reproduction, development, and aging. Results from experiments conducted beyond low Earth orbit will contribute to the safety of space exploration and address fundamental questions of life's potential beyond its planet of origin. Research campaigns will include a combination of core studies and innovative, PI-driven investigations. Multiple flight platforms—including free flyers and planetary bases—may support a range of manned and unmanned mission opportunities.

Strategies for Conducting Life Science Experiments Beyond Low Earth Orbit

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Abstract

Exploring worlds beyond Earth will require terrestrial life to survive and ultimately flourish in environments fundamentally different to those in which it has evolved. The effects of deep space and conditions on the surface of other worlds must be studied and compared to the Earth, to understand and reduce the risks to explorers, and to make full use of the broad research opportunities and scientific benefits offered by such unique environments. Though much is already known about adaptations to the space environment, key changes in terrestrial life may only be revealed over full life cycles and across multiple generations completed beyond Earth. The demands and potential risks of exploring and inhabiting other worlds necessitate a detailed understanding of these changes at all levels of biological organization, from genetic alterations to impacts on critical elements of reproduction, development and aging. Results from experiments conducted beyond low Earth orbit can contribute to the safety of space exploration, drive numerous social and economic benefits by extending our basic understanding of life on Earth, and address fundamental questions of life's potential beyond its planet of origin. Core research can use model organisms and human cell cultures to establish biological reference standards for each new space environment. These standards can enable comparisons across environments and form the foundation of efforts to predict, assess, and minimize biological risks to humans. Research campaigns can include a combination of core studies and innovative, PI-driven investigations. Multiple flight platforms -- including the ISS, free flyers, and planetary bases -- can be implemented to support a range of manned and unmanned mission opportunities.

Introduction

Space Life Science Program Prior to Apollo

Space life sciences research began 4 decades ago on the Gemini missions and currently continues on the Space Shuttle and International Space Station. Goals of the early space life sciences programs were simple in comparison to the complexity of experiments now incorporated onto Shuttle and/or Space Station payloads.

The series of Mercury missions (1961-1963) established that humans could successfully travel in space for brief periods of time. Missions ranged from 15 minutes to 1.5 days with a crew of 1 to collect human biomedical data on the stresses associated with a) the microgravity environment and b) with launch and re-entry.

The Gemini series of missions (1965-1966) conducted lunar landing verification tests. Missions ranged from several hours to 4 days with a crew of 2. Astronauts collected considerable biomedical data to determine the effect of space flight on human physiological systems. During the Gemini missions, the first life science experiments in developmental biology were conducted. Gemini 3 flew Sea Urchin eggs. The goal of this experiment was to determine the effects of the gravity on fertilization, cell division, growth and differentiation in a simple biological system. In this experiment, fertilized eggs were fixed at predetermined times during the course of the mission. Ground control specimens were also fixed according to the same timeline. Due to a hardware malfunction, this experiment was not completed on Gemini 3. On the Gemini 8 and 12 missions, a second set of developmental biology experiments flew. In this experiment, investigators determined whether fertilized frog eggs exposed to a microgravity environment would divide normally and differentiate into a normal embryo. Flight data from these missions showed that cleavage occurred normally in both the early and late stages. Furthermore, embryos fixed postflight showed the embryos had progressed into morphologically normal tadpoles.

Although the experimental results indicate gravity is not required for differentiation and morphogenesis of fertilized frog eggs, it is important to mention that these experiments used eggs which were fertilized on the ground. Ground based studies have shown that frog eggs are most sensitive to gravity between fertilization and first cleavage, which is prior to the start time of the Gemini 8 and 12 mission experiments.

Although the Apollo missions (1968-1972) landed humans on the Moon, life science experiments were never conducted on the lunar surface. Geology and physical sciences operations were the primary objectives of these missions. Some of the operations included; a) collecting lunar samples for subsequent analysis on Earth, b) setting up the Apollo Lunar Surface Experiments Package station (ALSEP) which sent lunar telemetry information back to Earth, and c) conducting extravehicular activities (EVA) on the lunar surface. Despite the fact biological sciences research was not conducted at the lunar surface, the Apollo 16 and 17 missions conducted the first radiation biology experiments in a lunar orbit. These experiments determined the effect of high energy cosmic particles on the growth and viability in various microbes. The collection of microbes, which included bacterial and fungal samples flew in the Microbial Ecology Evaluation Device (MEED). This device exposed the microorganisms to the sun's rays during the mission. Results from these investigations showed there were no statistical differences in microbial survivability between the flight and ground control groups. The first radiation biology experiment using a rodent model flew aboard the Apollo 17 mission. As with the microbal experiment, the rodent investigation was also interested in determining the effects of cosmic particle radiation. In this experiment, the flight group of rodents was implanted with plastic dosimeters to record the radiation received during the flight. Following the mission, the mice were evaluated for lesions and other physical damage. There were lesions in the scalp, olfatory epithelium damage and hemorrhaging in the middle ear of both the flight and control groups. Overall, there was no damage to body tissues due to high-energy particles in either group. The significance of the Apollo 16 and 17 experiments estimated the potential radiation hazards for man in space.

Space Life Sciences Program (Post Apollo)

The United States has not returned to the surface of the Moon since the Apollo 17 mission concluded in 1972. After the last mission, funding and interest declined for the lunar program. Despite the termination of the Apollo Program, NASA never abandoned the idea of sending humans to conduct research and explore other planetary surfaces such as the Moon and Mars. Over the past 20 years, NASA has written comprehensive reports on future missions and launched robotic missions to prepare for future manned missions beyond low Earth orbit (Beyond LEO) to destinations such as the Moon and Mars.

In 1992, the NASA Aerospace Medicine Advisory Committee (AMAC) released a report entitled "Strategic Considerations for Support of Humans in Space and Moon/Mars Missions" (1). The purpose of this report was to serve as a template guiding future NASA scientists, mission planners and policy makers to achieve NASA's goals of space exploration beyond our planet of origin (Mission from Planet Earth). This document served as a comprehensive blueprint containing critical life science questions that could be answered on a variety of research platforms including; space labs, the international space station, a lunar base or on free flying satellites. Additionally, this report highlighted the life sciences disciplines benefiting from Beyond LEO research. These areas include exobiology, cell and developmental biology, neuroscience, and regulatory physiology (including cardiopulmonary and musculoskeletal systems). Within the Executive Summary, AMAC emphasized the crucial role of Beyond LEO life sciences research to support successful human exploration missions by:

- Implementing robotic precursor missions with life sciences participation to characterize radiation and resources available for life support and for designing planetary protection protocols

- Maintaining a balanced synergistic core life sciences program, which provides additional resources necessary to enable Moon and Mars missions

In 1997, NASA released another critical planning document entitled "Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team" (2). This document outlined in detail the overall mission scenario and timeline associated with human missions to Mars. Beyond LEO research is important in fulfilling 2 of the 3 overall goals for Mars Surface Mission Activities by:

- Conducting applied science research using Mars resources to augment life-sustaining systems

- Conducting basic science research to gain new knowledge about the solar system's origin and history

Beyond LEO research will address these surface activities goals by:

- Investigating the biological adaptation of representative plant, animal and microbial species to the Martian environment over multiple generations

- Providing evidence to answer the question "Has Mars been a home for life?"

In 2003, NASA released a lunar-specific document entitled " Lunar Surface Reference Missions: A Description of Human and Robotic Surface Activities" (3). This document provided an overview of surface activities to be conducted on the Moon and their relevance to other NASA goals including long-term space habitation and exploration Beyond LEO.

Beyond LEO research plays a critical role in the success of long-term occupation of a lunar outpost. Data gathered from Spacelab and ISS experiments partially address the overall effects of a space environment on biological organisms. The more effective and comprehensive answer to long term habitation comes from survival, adaptation and change experiments with bacteria and simple eukaryotic organisms.

Within the last decade, NASA has launched robotic missions to visit the Moon again. In 1994, the Clementine spacecraft discovered possible evidence for water ice on the Moon. In 1998, the United States launched the Lunar Prospector mission. This robotic mission was the result of a 1992 Lunar Exploration Science Working Group which drafted a list of the most pressing unanswered questions from the lunar science community. However, the scientific objectives focused only on geology and/or physical sciences. The critical science objectives were; a) prospect the lunar crust and atmosphere for potential resources, b) map the moon's gravitational and magnetic fields and c) learn more about the size and content of the Moon's core. Although the Lunar Prospector mission did not conduct life sciences experiments, the Prospector did find water ice scattered on both the North and South Poles of the Moon.

Several robotic missions have also focused on Mars over the last 30 years. The first successful landings of a robotic spacecraft began in the 1970s with the Russian Mars missions (1971-1973) and US Viking Missions (1975) and continued in the 1990s with the arrival of the Mars Pathfinder (1996). As seen in the lunar robotic missions, these missions emphasized geology and/or physical sciences research including mapping and photography of the foreign planetary surface. The latest robotic missions to land on Mars were the Twin US Mars Exploratory Rovers (MER). The landings were on January 3 and 24, 2004. The purpose of this robotic mission is to determine if water ever existed on the Martian surface.

NASA Visions and Goals

NASA's life sciences research programs are now administered within the Office of Biological and Physical Research (OBPR). OBPR is one of 5 Organizing Enterprises responsible for achieving NASA's overall goals and visions. In 2003, OBPR conducted a series of Enterprise Roadmap workshops to outline its future direction, which includes research questions and topics for space sciences investigations. The major OBPR questions are

- How can we assure the survival of humans traveling far from Earth?

- How does life respond to gravity and space environments?

- What new opportunities can research bring to expand understanding of the laws of nature and enrich our lives on Earth?

- What technology must we create to enable the next explorers to go beyond where we have been?

- How can we educate and inspire the next generation to take the journey?

These questions have been incorporated into the OBPR Research Enterprise Strategy, meant to serve as a guide to NASA's research plan for the next 15 years (4).

Beyond LEO Life Sciences Research

In 2003, NASA Space Architecture funded this conceptual study into strategies for conducting life science experiments beyond low Earth Orbit (5). One central goal of Beyond LEO life sciences research is to study life at all levels of biological complexity over multiple generations in a variety of space environments. Although the number of generations required to determine the effects of a space environment on reference organisms is not currently known, previous ground-based experiments using Drosophila and mice have shown physiological differences appear between stress-related and control populations after 10 generations (6,7).

Beyond LEO research will

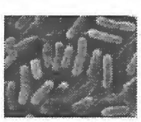
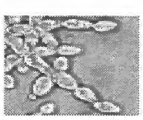
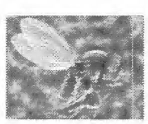
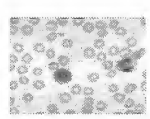
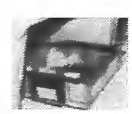
- Help answer the question "How specific is life to its planet of origin?"
- Help access overall biological risk of long-term human space exploration.

Beyond LEO research questions can be addressed using 2 different approaches: core and principal investigator-led (PI) research. Core research will use NIH/NASA model organisms, which include human cells in culture, to establish biological reference standards for each space environment. Model organisms have been widely used and accepted for the study of fundamental biological processes on Earth for several reasons, including:

- Availability
- Ease of Handling
- Small Organism Size
- Rapid Development
- Relatively Short Life Cycle
- Completed Genomic Sequencing

The model organisms that can be used include:

- Bacteria (*E coli*)
- Yeast (*S cerevisiae*)
- Nematodes (*C elegans*)
- Insects (*Drosophila*)
- Plants (*Arabidopsis*)
- Human Cells in Culture
- Rodents (*Mus musculus* -Mouse, *Rattus norvegicus* -Rat)

PI-led research, also known as pioneering research, will use different experimental organisms and approaches compared to core research. PI-led research can be directed by the scientific community and based on hypothesis- driven questions.

There are several different Beyond LEO research locations, including:

- High Earth Orbit (1500-36,000 km)
- Moon (384,000 km)
- Libration Points (1.5 million km)
- Mars (78 million km)

These environments vary in their gravitational field, radiation levels, magnetic fields and day/night cycles. Conducting life science research in these different environments will require the use of specific research platforms suitable for the individual location. Each platform can provide different critical information on the overall effects of the space environment on biological organisms. The various research platforms include;

Research Platform	**Gravitation Level**	**Radiation Level**	**Data Collection**
Ground-based Labs	1g	Low	Baseline data for proposed flight experiments
Space Shuttle	10^{-6}g		Early adaptation to the microgravity environment
International Space Station	10^{-6}g		Long -term adaptation to the microgravity environment (multi-generations)
Free Flyer	Varies	Varies	Long duration data on variable gravity, orbital and planetary environments
Inflatables	Varies	Varies	Multi-generation data on variable gravity, orbital and planetary environments
Lunar Base	1/6g	High	Multi-generation data of Lunar environment
Mars Base	1/3g	High	Multi-generation data of Mars environment

Beyond LEO Research Risks and Mitigation Strategies

Conducting life sciences research Beyond LEO is inherently full of risk. There are several categories of risk conducting Beyond LEO research

- Mission
- Operations
- Communications
- Crew Health and Safety

In order to conduct Beyond LEO Life Sciences experiments safely, considerable planning and preliminary work must be done. NASA has already started several projects focusing on the various aspects required to achieve mission success. The current projects include a Lunar Testing Campaign, the Free Flyer Initiative and Space Architecture concepts.

Lunar Testing Campaign is a NASA center-wide effort to reduce mission risk to Mars. This campaign is dedicated to identifying and evaluating potential risks from all mission perspectives. Through various testing venues on Earth, in LEO, at the Lunar surface, and at the Martian surface, risk mitigation strategies can be developed and tested to ensure a successful human mission to Mars.

The proposed Free Flyer Initiative is also a NASA center-wide effort to expand the research capabilities of OBPR Beyond LEO. Free flyers are unmanned, free flying spacecraft, which can sustain long duration microgravity. There is no crew involvement; therefore research can be conducted in these vehicles can be under extreme conditions.

Space Architecture evaluates designs for mobile and stationary bases at Beyond LEO locations. The following topics must be addressed when designing mobile or stationary structures.

- Automated assembly and deployment
- Configuration and methods for connecting modules
- Radiation (and other environmental) protection
- Mission duration
- Crew habitability
- Bioregenerative life support capability
- Science experiment requirements
- Technology requirements

Conclusion

Beyond LEO Research Benefits

Throughout its evolution, life on Earth has constantly been exposed to the force of gravity. Because of its consistent presence, the effect of gravity on life is a question of fundamental and substantial value. Space exploration provides the only environment in which the force of gravity can be changed or completely removed to address such critical scientific questions. Beyond LEO missions will provide the opportunity to conduct research, foster science education, and spark the imagination of scientists and the public. Successfully conducting Beyond LEO research requires multiple research platforms at increasing distances and time durations from low Earth orbit. Using this approach, on-orbit and/or planetary observation and analysis can be used to modify experimental parameters of ongoing or sequential experiments.

There are several reasons why Beyond LEO life science research is critical. Beyond LEO research can:

- Validate and extend results of previous microgravity research conducted on the Space Shuttle and ISS
- Provide information on the overall long-term survival, habitation and reproductive capabilities of biological organisms in reduced gravity and high radiation environments
- Provide preliminary information on how human crews will respond to both long-term space flight, reduced gravity and high radiation environment
- Reveal features of terrestrial life not possible to see on Earth

- Reveal the first empirical evidence whether life can evolve beyond its planet of origin
- Provide the first genomic transcription of how life adapts to new worlds
- Provide the first production of plants and food beyond Earth
- Provide the first conception and birth of a mammal beyond Earth
- Provide a unique opportunity to develop technologies which can also benefit humans on Earth

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