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Expanding Astrobiology: The Case for a Lunar Biorepository

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Abstract

As space exploration advances, Earth's resources will be essential in supporting ourexpanding presence beyond the planet. At the same time, global conflicts, environmental change and natural disasters are threatening ecosystems and biodiversity,putting the integrity of Earth's essential ecosystems at risk. These converging challenges underscore the urgency of developing innovative strategies to conserve Earth's biodiversity to protect ecosystems. Astrobiology seeking to understand life's origins, limits, and potential beyond Earth plays a key role in this effort, offering vitalinsights for preserving Earth's most vital species while also providing critical assetsfor exploring and working in space. Recently, a Lunar Biorepository was proposedthat would hold cryopreserved samples from among the most critical species on Earth. The present article addresses the potential benefits, challenges and solutionsof a Lunar Biorepository and how this would support Astrobiology's emerging roleas a cross-cutting pillar of NASA and other space agencies. The technology and science needed to build this biorepository and its ability to support other criticalplanned missions enhances the goals of the field of Astrobiology, specifically relatedto extreme cyro-environment adaptation as well as preservation and detection ofbiosignatures. We summarize here how the biorepository would be created andwhat species would be selected. We also consider additional topics on how a Lunar Biorepository would support new technology, how we will develop a multipurposepayload, site selection and biorepository construction, governance and ethics whilestrengthening community and fostering cross-discipline collaboration. To supportlife beyond Earth, we must understand how life can exist in space and be be transported to other environments and be sustainable in space. A Lunar Biorepositorywould not only advance astrobiological research but also help safeguard Earth's bio-diversity.

Keywords: Biorepositories; Endangered Species; Governance

Introduction

Earth's resources — people, materials, energy, water, and food — are what support our expansion to work and explore space. At the same time, Earth's ecosystems and natural resources are being compromised by over-extraction of terrestrial and marine assets, natural disasters such as fires and extreme weather events, and socio-economic threats, such as wars [1, 2]. These events are risking Earth's biodiversity and the integrity of essential ecosystems [3]. Innovative strategies are urgently needed to conserve Earth's biodiversity and protect fragile ecosystems. One such strategy involves the development of biorepositories in space, which could significantly help and expand the scope of astrobiology. Traditionally, astrobiology has focused "on the origins, early evolution, distribution, detection, and future of life in the universe" [4]. In that context, the preservation and detection of biosignatures are crucial aspects that have received limited attention in studies focused on the cryo-environments of icy worlds in our solar system and beyond. Astrobiology can also play a pivotal role to help maintain Earth's most important species while providing critical assets for exploring and working in space. As humans embark on long-duration space missions and begin to explore or inhabit other planets, they will need the capacity to feed themselves and terraform their local environment. A Lunar Biorepository would house comprehensive collections of cryopreserved seeds and microorganisms to be transported safely through space. In this context, we propose a Lunar Biorepository as a cross-cutting concept that redefines and expands astrobiology's role in both space exploration and Earth conservation.

We recently proposed a passive Lunar Biorepository [5] designed to safely hold cryopreserved samples from some of the most critical species on Earth for extremely long durations, potentially centuries or longer. These frozen assets require preservation at liquid nitrogen temperatures – conditions that are not naturally sustained anywhere on Earth. Instead, these critical species could be stored in the south pole of the Moon where areas, such as Permanently Shadowed Regions (PSRs) [6,7], remain at liquid nitrogen temperatures indefinitely. Moreover, on Earth, major biorepositories are near large population centers and thus vulnerable to threats, whereas a biorepository on the Moon would be highly protected. This effort would parallel the Svalbard Global Seed Vault [8]; this passive biorepository requires little maintenance staff or energy, yet holds Earth's most important agricultural seeds in case of catastrophic collapse of crops.

The Lunar Biorepository would initially store cryopreserved fibroblast cells that are found in the skin of most animals and can potentially be transformed into multiple cell types, including spermatozoa and oocytes [9]. In the future, other critical species and cell types can be added to the repository. When thawed, these powerful cells can be used to generate whole organisms [9]. Further, the Lunar Biorepository could store biomaterials for food, filtration, microbial breakdown, and ecosystems engineering for extraterrestrial endeavors. Residing under approximately two meters of regolith to help reduce the threat of radiation [10], these cryopreserved samples could remain frozen-and-alive for centuries. As needed, they could be returned to Earth to help re-diversify animal, plant, or microbial populations as well as leveraged for environmental conditioning of planetary environment.

The current benefits of space exploration center on increasing scientific discovery, advancing technology, inspiring future generations, and creating new career pathways. These efforts are focused on enhancing knowledge for further space exploration. A Lunar Biorepository will not only advance our understanding of life in space but also serve as a valuable and achievable driving goal that benefits life on Earth and humanity as a whole in the form of a biorepository archiving samples and their genomes from key species to serve as a source for biotechnology and innovation and a hedge against ecological disaster and species diversity loss on Earth.

Methods and Results

Creating a Biorepository

We propose to create a cryopreserved biorepository of fibroblast cells, plant cells and microbes representing most of the species supporting life on Earth. The technology to extract, cryopreserve, and reprogram fibroblast stem cells to produce new, living organisms [11] is a novel approach for space science. The technology that would result from this effort has implications for advancing other astrobiological initatives, such as understanding how complex organisms and biosignatures can survive and adapt to cryogenic environments, such as found on icy worlds of our solar system and beyound.

Additionally, cryopreserved cells must be supported through robust engineering and space-related technology. The Biorepository will be largely constructed, stocked and maintained through unmanned space craft and dedicated rovers [12].

Comparative studies of cryopreserved samples in this Biorepository on the Moon and parallel cryopreserved samples preserved on Earth will advance our understanding of cellular and evolutionary processes and how cells respond to transport and long-term holding in space, especially the effects of microgravity and radiation. Because it is located on the Moon, the Lunar Biorepository may be protected from Earth-based disasters. As we look to the future, this biorepository may be able to support living systems on the Moon and during space flight as well as assist terraformation on extra-terrestrial planets. It will also provide protection against species extinction life on Earth.

Species Selection

Species to be included in the Lunar Biorepository may be “ecological engineers (that modify their environments), pollinators (that support the production of food), extreme environment fauna (that live in extremely warm, cold or acidic environments), primary producers (that support the web of life on Earth), temperate to cold water fishes, threatened and endangered animals (those in danger of extinction in the next 50 years), important organisms for maintenance of humans during space flight and terraformation, ancestral wild relatives (genetic relatives of modern agriculturally important animals) and species of cultural importance” [5]. International partners will need to consult broadly to select these multiple faunal and floral groups. Our initial focus will be the selection of fish species from across the US using criteria based on the science of systematics using the methods for fish collections of the National Ecological Observation Network (NEON) [13]. This broad effort will ultimately encourage the participation and collaboration of representatives from each participating Nation.

Multipurpose Payload System

We are currently designing a payload system that can maintain biological samples at liquid nitrogen temperature (-196°C) while transporting the samples to and from the lunar surface that will also protect them from radiation during transit. Ideally, this payload would be used to bring cryopreserved samples to the Moon for the Biorepository and return to Earth with cryopreserved lunar samples from PSRs that have frozen water. Developing the capability to retrieve core samples of frozen volatiles from PSRs on the Moon and volatile-bearing sites on Mars and to deliver them in pristine states to modern curation facilities on Earth would be critical to understanding the evolution and sources of these water samples. Ideally, the samples delivered to the Moon’s surface would be secured and delivered by rovers to the Biorepository.

Site Selection and Building the Biorepository

The Lunar Biorepository will likely be sited at the Lunar South Pole in a PSR. As noted above, some PSRs may have water within them and are very deep (e.g., Shakleton Crater is 4.2 km deep); they would not make ideal candidates for a biorepository because of the political and planetatry protection concerns over those areas. Nevertheless, there are multiple candidate PSRs that are dry and potentially ideal for our purposes. We will use data similar to those collected with HORUS (Hyper-effective nOise Removal U-net Software) [7] to find a PSR that is dry, not too deep, and with sloped edges allowing rover access.

Constructing the biorepository will depend upon novel construction methods for the Moon using regolith as the fabrication material, in ways that include solidification, sintering, bonding solidification or confinement formation [14] with rovers to construct the facility. Many of the PSRs in the Lunar South Pole have impact craters anywhere from 15 to 100 m in diameter and 2.5 to 16.7 m deep [7]. Rovers could potentially roof the impact crater using one of the construction methods mentioned above and then place meters of loose regolith on top to protect from long-term radiation threats to the cells [15]. The success of this approach requires advancing rover technology including testing of their capabilities here on Earth before being sent to the Moon [16].

Governance & Ethics

One of the more challenging components of the Biorepository will be crafting the agreements that govern it. As a beginning model, we can consider the governance structure and process instituted for the Svalbard Global Seed Vault [17] based in the Norwegian Arctic. This is an international partnership supported by multiple biorepositories around the world. However, governance for the Lunar Biorepository should allow cooperative oversight and removal of samples for collective use if needed for space exploration or in the event of ecological disaster on Earth. Crafting ground rules for that cooperation should anticipate the potential for conflict on Earth and should strive to create processes that will continue to work in the face of conflict.

An additional challenge is that the Outer Space Treaty of 1967 [18] states that no country or entity can claim territory on the Moon. Securing a site (or two sites if we build a parallel repository to offset risk) will need to address this issue. International negotiations and agreements are critical for this project to develop and succeed. Moreover, there are many cultural groups that hold the Moon sacred, including Native Americans such as the Navajo Nation, and the Nepalese, among others [19]. Their partnership will be important element in developing governance.

Strengthening Community & Fostering Cross-Discipline Collaboration

Our proposed Biorepository will be a new focus for astrobiological discoveries and achievements. To address the evolving needs of the community, this concept will promote collaborative research and exploration efforts across broad scientific and programmatic pursuits, spanning disciplines such as Earth Science, Biological, Physical, and Social Sciences, Engineering and Cyberinfrastructure, Artificial Intelligence, Ethics, Law and Astrobiology. We anticipate that this will be a decades-long process to envision and create this Biorepository with multiple institutions worldwide contributing to the effort and that this Biorepository has the potential to last many centuries. We predict that the concept of a Lunar Biorepository will engage space-related stakeholders and community members positively, as the initial concept of a Lunar Biorepository [5] was widely well received by science and the public alike. It garnered over 194 mentions in various news outlets worldwide and 28,649,717 research outputs (AltMetrics).

Discussion

There are challenges in "securing Earth's biodiversity and supporting human exploration and terraforming of other planets [through] long-term storage on the Moon [5]". The benefits of a Lunar Biorepository are many.

It will: 1) provide a testbed for cryopreserving organic and biological materials in space environments, which will inform theories of material transfer between planetary bodies, their detection as biosignatures and aid in the development of technologies for long-term preservation of biological material for bio-signature recovery for robotic missions and long-duration crewed spaceflight;

2) maintain cryopreserved fibroblast stem cells frozen and alive for potentially hundreds of years, and if needed, those stem cells can be transformed into eggs and sperm to reproduce species;

3) maintain cells cryopreserved transported to-and-from the Moon, allowing for cryopreserved samples from the Moon to travel safely to Earth e.g., to help with the understanding of the origins of frozen water on the Moon;

4) help maintain healthy Earth Ecosystems because it is a hedge against extinction pressures on Earth, such as diseases and natural disasters, etc.;

5) be cost-effective, because it will preserve biodiversity and genetic diversity of thousands of species in a passive biorepository with a small footprint on the Moon;

6) advance studies comparing cellular and evolutionary processes in cryopreserved lunar cells with those processes in parallel samples on Earth to elucidate how cells respond to long-term holding in space, thus supporting biotechnology and innovation;

7) support space exploration (e.g., by providing a source for cells needed for planetary environments conditioning and food resources during extended flights and human habitation on the Moon);

8) unify nations and help promote peace through scientific diplomacy because it will engage all nations at many levels of society for decades in the selection, collection, processing, and storage of species;

9) leverage the strengths of the NEON and the Smithsonian, among other institutions, for collecting cells, data management and acquisition, and cryo-storage;

10) support the Earth and all humanity.

The challenges and the potential solutions for a Lunar Biorepository include: i) radiation damage, which can be mitigated by barriers such as covering the biorepository with meters of regolith; ii) maintaining liquid nitrogen temperatures at all times for the samples, which can be offset by use of cryo-engines [20] during transit and centering our activities at the South Pole of the Moon in or near PSRs [21]; iii) the use of PSRs could be sensitive due to planetary protection concerns, but some areas, such as dry PSRs, that may maintain the same low temperature may be of less concern, but must be identified through international consultations; iv) micro-gravity may impact cells; little is known about the effect of micro-gravity on biological material once it is frozen; and, v) organizing, managing, and protecting a Lunar Biorepository from Earth will be an enormous challenge that will depend upon careful consideration of ownership and long-term governance issues.

This project is monumental. Yet we have important pieces in place and are ready to begin the next phases of discussion, planning, collection, testing, design, and importantly, collaboration across the interdisciplinary scientific community. Initially, we would use existing collection protocols to gather material for the biorepository, such as those for the U.S. National Science Foundation's NEON [13]. We have identified robust space-proven packaging to hold the cryopreserved cells in stasis on the Moon [22] and have designed a payload with a space-proven cryo-engine [20] that can maintain the cells at cryopreserved temperatures from lift-off-to-landing on the Moon. We project that much of the work to build and maintain the Lunar Biorepository could be accomplished through unmanned spacecraft, assisted by rovers and robots [12]. Finally, this project is a way to evaluate preservation and retrieval mechanisms for returning newly discovered life to Earth. Those will have to travel great distances with minimal energy or human intervention, so the passive aspects of the Lunar Biorepository could be a testbed for future, distant retrievals.

We look hundreds of years or even longer into the future where this biorepository can support many space missions and will also provide a hedge against species' extinction on Earth. If we want to support people and life beyond Earth, we must prepare to understand how life can exist in space and to be transported to other regions. This Biorepository is a major step toward creating the mechanism and understanding this process.

Conclusions

To support human life beyond Earth, we must first understand how life can exist in space and be transported to new environments. Developing a Lunar Biorepository offers valuable insights into astrobiological processes, especially in extreme environments like ocean worlds, which may be more common in the Universe than rocky planets like Earth. Looking hundreds of years into the future, such a biorepository could support numerous space missions and may serve as an insurance policy against species extinction on Earth. For humans to undertake long-duration space travel and settle on other planets, they will need the means to grow food and terraform their local environment. A Lunar Biorepository, housing a diverse collection of cryopreserved seeds, cells, and microorganisms, would also provide these essential resources. Ultimately, establishing a Lunar Biorepository represents a crucial step toward enabling sustainable exploration and deepening our understanding of life beyond our planet.

Conflict of Interest

The authors declare no conflict of interest

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