Life Beyond Earth: Microbial Endurance in Space

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***Abstract*—Microorganisms rank among Earth's most ancient and versatile life forms, and they are now aiding our quest to understand life beyond our planet. These minuscule entities have demonstrated their ability to thrive in extreme conditions such as deep-sea vents, acidic springs, and ice tundras and extraterrestrial adaptation. Even more remarkably, they have shown resilience against the harsh conditions of space, including radiation, vacuum, freezing temperatures, and weightlessness. For decades, scientists have been sending microbes into space, subjecting them to both actual and simulated space environments. Certain species, like *Bacillus subtilis* spores and *Cryomyces fungi*, have survived for extended periods, especially when shielded by dust or rock layers. These findings support the interesting idea of interplanetary microbial transfer, which says that life might move between planets by traveling on space rocks. They exhibit altered growth patterns, form more robust biofilms, and sometimes develop increased resistance to antibiotics. On the International Space Station (ISS), some bacteria have evolved in ways that could pose risks to astronaut health or damage equipment. Additionally, the unique conditions of space can weaken astronauts' immune systems, making these microbial changes even more worrisome. Nonetheless, microbes are not just passive travellers in space; they also serve as valuable tools in guiding scientists in creating more effective methods for detecting life on other planets. Cutting-edge technologies such as microbial fuel cells, lab-on-a-chip sensors, and antibody-based detectors are being developed using microbial behaviour as a model, harnessing their resilience to support future space exploration and life detection efforts.**

***IndexTerms*—Microbial survivability, Space Adaptation, Interplanetary microbial transfer, International Space Station, Cutting edge technologies**

I. INTRODUCTION

Microorganisms began evolving on Earth more than 2.5 billion years in the past. (Cavalier-Smith,T. 2006). The first microscopic observation of tiny microorganisms is attributed to Antonievan Leeuwenhoek discovery who described them as ‘animalcules. Extremophiles are microbes that live in extreme places like boiling vents, acidic hot springs, icy polar zones, and deep underground (Merino N. *et al*., 2019). These organisms show resilience to heat, cold, pressure, radiation, and starvation. The harsh space environment including microgravity, UV radiation, vacuum, and cosmic rays significantly influences microbial growth, survival, and cultivation, making it a key area of study. (Nandhini B, 2021). Because of their survival capabilities, extremophiles are vital to the study, of astrobiology, which looks for life beyond our planet. Space, characterized by extreme conditions such as radiation, vacuum, and microgravity, serves as a natural setting for testing the limits of life. Researchers have isolated microbes from space equipment and the ISS (Checinska Sielaff, A. 2019). A study aboard the ISS found reduced microbial diversity affecting astronaut immunity (Smith & Johnson, A. 2025). *Niallia tiangongensis*, isolated from China's Tiangong station, showed adaptations for surviving microgravity (Yuan, J. *et al.,* 2025). Most space microbes are of prokaryotic origin, known for adapting and colonizing extreme environments.

By studying fermentation and DNA repair in tardigrades, scientists gain a better understanding of microbial processes under space conditions (Rizzo *et al.,* 2025). Microbial behavior in microgravity, vacuum, and cosmic radiation is the core focus of space microbiology. NASA’s O/OREOS mission in

2010 included the SESLO experiment testing Bacillus subtilis spores' survival in orbit. Despite harsh conditions such as radiation and temperature shifts, the spores demonstrated viability and were able to germinate and grow, though more slowly than under terrestrial conditions (Nicholson, WL. *et al*., 2011). A study conducted on microbial samples exposed to space environment for a period of 18 months by the European Space Agency's EXPOSE-E platform on the International Space Station revealed that while UV radiation killed exposed spores, those protected by dust or rock analogs remained viable upto 100%. This suggests microbes could survive interplanetary travel if shielded, supporting lithopanspermia theories (Rabbow, E. *et al*., 2012; Wassmann, M. *et al*., 2012). The microbes that survived in space showed active stress responses, including DNA repair, oxidative damage control, and protein protectiondemonstrating their ability to resist space-related stressors (Moeller, R *et al.,* 2012). These findings confirm that microbes can withstand extreme space conditions while preserving vital biological functions. These findings are crucial for designing life-support systems, contamination protocols, and sustainable space exploration (Nicholson, WL. *et al*., 2011).

II. MICROBIAL RESILIENCEIN THEFACE OF SPACE EXTREMES

Understanding how microbes survive in space is critical for both planet preservation and the success of long-term space missions. Vacuum, radiation, dehydration, microgravity, and dramatic temperature variations all pose significant hurdles to living in space, putting biological systems to the test. Studies suggest that bacteria, particularly spores, can withstand these harsh circumstances if adequately protected. Spores from *Bacillus subtilis* and *Bacillus pumilus* can tolerate vacuum and dehydration if they are protected from UV radiation or contained in physical barriers such as multilayers, salts, or biofilms. Experiments using the LDEF and EXPOSE-E platforms on the ISS demonstrated that spores enclosed in multilayers or incorporated into materials retain viability even after long-term exposure to space. (Pacelli, C. *et al*., 2024). These protective arrangements reduce radiation exposure, supporting the concept of microbial transfer between planets, a significant aspect of the panspermia theory (Abrevaya, XC. *et al.,* 2023). In addition to dehydration and radiation, the extreme temperature variations in space can threaten microbial structures. However, such conditions may lead to natural lyophilization, a process that preserves microbes by dehydrating them. High-altitude balloon experiments have demonstrated that while solar radiation can deactivate exposed microbes, their survival rates improve in protected environments (Khodadad, C. L. *et al.,* 2017). The resilience of extremophiles like *Deinococcus radiodurans* under vacuum-UV exposure, particularly within halite crystals, suggests that mineral substrates can act as protective shields. These findings expand the known limits of microbial resilience and have implications for contamination risks and the spread of life across different celestial bodies (Abrevaya, XC. *et al*., 2023).

III. MICROBIAL ADAPTATION AND MUTATION IN SPACE

Life on Earth has evolved over billions of years under stable planetary conditions. When microbes are launched into space, they adapt and sometimes thrive in this alien environment. Studying the growth dynamics of microbes in space is essential to understand various factors related to astronaut safety and health, the success of mission operations at multiple levels, and the ongoing search for extraterrestrial life. The space environment is characterized by extreme conditions, including microgravity, high radiation levels, and vacuum and drastic temperature variations. (Cockell, CS. *et al.,* 2000). These types of stressful conditions force microbes to adapt uniquely. The International Space Station (ISS) provides a special environment where microbes from humans and the surroundings live and change together (Venkateswaran, K. *et al.,* 2014).

The growth of *Salmonella typhimurium* and *Pseudomonas aeruginosa*, is quite affected due to microgravity existing in space environment (Nickerson *et al*., 2000). These changes also impact their genes and proteins, which influence how they process energy and respond to stress (Wolf, DA. *et al.,* 2012). Bacterial biofilms have long been present on spacecraft, posing health risks to astronauts and threatening food and water supplies. In microgravity, these biofilms adapt by altering gene expression,

becoming more resilient and potentially more harmful. Understanding their impact is crucial for the safety and success of long-duration space missions. (Landry KS, *et al*., 2021).

In space, cosmic rays and solar particles damage microbial DNA, increasing mutation rates and evolution potential (Amoozgar, MA. *et al*., 2019). Space conditions can make microbes more antibiotic-resistant or virulent (Mortazavi, SM. *et al.,* 2020). The IIT-NASA team**,** in collaboration with Dr. Kasthuri Venkateswaran**,** a senior research scientist at NASA's Jet Propulsion Laboratory (JPL), has identified a mutated strain of *Enterobacter bugandensis* aboard the International Space Station (ISS)**.** The study also found that space-evolved *E. bugandensis* strains not only survived long-term on the ISS but also thrived alongside other microbes, possibly supporting their persistence. Unique space conditions seem to drive these genetic changes, highlighting the urgent need for better microbial monitoring and containment in future Moon and Mars missions. (India Today Science Desk, New Delhi, 2024). Spacecraft environments enable bacteria to acquire new traits quickly through horizontal gene transfer mechanisms (Schuerger, AC. *et al.,* 2014). While these microbial changes present potential risks, they also highlight the resilience of life and its possible ability to survive elsewhere in the solar system. Understanding space microbiology helps protect astronauts, maintain spacecraft, and explore potential extra-terrestrial life. All these changes aren't just fascinating they're potentially dangerous. But they also offer insight into life's resilience and hint at how life could survive, or even spread, across the solar system. Improved knowledge of microbial behaviour in space supports astronaut safety, spacecraft maintenance, and the broader quest to find life beyond our planet (Blachowicz A, *et al.,* 2022; NASA.gov, 2022).

IV. MICROBES AS MODELS IN THE EXPLORATION OF LIFE BEYOND EARTH

The study of microbes is essential to astrobiology's quest to find extraterrestrial life. Microbial endurance in extreme settings offers insight into potential life on Mars, Europa, and other celestial bodies (Rampin, M. 2023). Experiments involving microbial exposure to space environments characterized by radiation, vacuum, and extreme cold have revealed remarkable survival capacities. Fungi such as *Cryomyces antarcticus* and *Bacillus subtilis* spores have survived both simulated and real space journeys. (Onofri, S. *et al.,* 2018). Experiments like EXPOSE and Tanpopo at international space station showed that some microbes can survive for long periods in space, especially when covered by other cells or dust (Ott, E. *et al.,* 2020). These results help scientists create better tools to find life and ensure we don't accidentally spread Earth microbes to other planets. By directly detecting microbial activity on other worlds, technologies such as microbial fuel cells may one day aid in the detection of life signs. (Abrevaya XC, 2010). Microbial models are essential tools in astrobiology, helping to refine strategies for detecting life beyond Earth. By studying the metabolic processes and survival strategies of microbes on Earth, scientists can better understand how life might manifest on other planets. The presence of methane on Mars is particularly intriguing because it might point to microbial processes, given that some microbes generate methane naturally.

V. MICROBIAL INFLUENCES ON ASTRONAUT HEALTH AND MISSION INTEGRITY

Human spaceflight presents various health challenges for astronauts attributed to harsh conditions in microgravity and increased exposure to radiation. Notable physiological effects include the loss of muscle mass and bone density; astronauts can lose approximately 1% to 2% of bone density monthly while in space, which significantly impacts their skeletal health post-mission. Astronauts experience cardiovascular alterations during spaceflight, and these changes in blood volume can cause orthostatic intolerance dizziness or fainting on returning to Earth's gravity (Hughson, RL. *et al.,* 2017).The radiation encountered during space missions is another critical risk factor. Astronauts are subjected to higher levels of ionizing radiation from cosmic rays and solar particle events. This exposure amplifies their cancer risk and may induce cognitive impairments over time (Khodadad, C. L. *et al.,* 2017; Maria, J. *et al*., 2023). Studies have shown that radiation can contribute to cognitive decline through complex interactions in the brain (Greene-Schloesser, D. *et al*., 2013).

Long-duration space missions introduce intricate microbial risks alongside notable physical health challenges for astronauts. The confined environment of spacecraft fosters the growth of opportunistic pathogens arising primarily from the crew members themselves, which can subsequently develop resilient biofilms on various surfaces, equipment, and water systems (Morrison, MD. *et al*., 2021). These biofilms can compromise astronaut health by enhancing pathogen virulence and antimicrobial resistance, posing considerable threats not just to crew well-being but also to vital hardware through mechanisms such as corrosion and mechanical blockage.

Moreover, studies indicate significant shifts in astronauts' microbiomes during spaceflight, characterized by reduced microbial diversity and an increase in antibiotic resistance genes. Such changes can lead to immune system dysregulation in the microgravity environment (Tesei, D. *et al*., 2022). For instance, the presence of multidrug-resistant *Enterobacter bugandensis* aboard the International Space Station (ISS) exemplifies concerning adaptations and mutations that can occur in a closed environment (Morrison, MD. *et al*., 2021). Moreover, the highly sanitized environment of spacecraft may unintentionally reduce astronauts' exposure to beneficial microbes, increasing the risk of chronic conditions like inflammation and skin infections (Turroni, S. *et al*., 2020).

VI. TECHNOLOGICAL APPLICATIONS AND FUTURE DIRECTIONS

Astrobiology drives technological innovations like the microbial fuel cell (MFC), which detects life by measuring electric currents from microbes. MFCs produced higher electricity with active microbes versus sterile samples, allowing detection through electrical signals (Abrevaya, XC. *et al*., 2010). By monitoring current fluctuations linked to light exposure, these devices can detect photosynthetic microorganisms, supporting their application in life-detection efforts on Mars or Europa (Figueredo, F. *et al.,* 2015). Lab-on-a-chip devices can detect biological molecules from a single liquid drop. The SOLID detector uses antibodies to recognize life-associated molecules, tested in Mars-like environments (Parro, V. *et al.,* 2008). The LOCAD-PTS system on the International Space Station enabled real-time microbial contamination testing. Astrobiology is moving toward creating small, smart biosensors that can find signs of life and adjust to their surroundings. Scientists are also using synthetic biology to design sensors that can work on harsh planets, helping us search for life beyond Earth.

VII. CONCLUSION

Microorganisms have showcased the extraordinary resilience and adaptability of life. By surviving the vacuum of space and withstanding harmful radiation, these tiny life forms challenge our understanding of life's boundaries. Extremophiles, in particular, inspire new possibilities for how life might endure on other planets—and even suggest that life could travel between celestial bodies, protected by rock or dust, as proposed by the theory of lithopanspermia. Experiments on space missions like O/OREOS and EXPOSE-E have revealed that, under the right conditions, microbes can not only survive but remain metabolically active repairing themselves and continuing to grow. Yet, their presence in space is not without concern. In the closed environment of a spacecraft, microbes brought by humans can adapt, becoming more resistant or forming tough biofilms that threaten astronaut health and may damage on board systems. As we look ahead to long-term missions to the Moon, Mars, and beyond, understanding how microbes behave and evolve in space is vital to ensuring crew safety and equipment reliability. At the same time, these microorganisms are proving to be valuable allies in our search for extra-terrestrial life. Their survival strategies guide us in identifying where and how to look for life on other planets.

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