The Future of Space Exploration

Course Guidebook

Ariel Ekblaw, PhD

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1

Innovating the New Space Frontier

THE VASTNESS OF THE UNIVERSE OFFERS INNUMERABLE things to discover, questions to ask, and problems to solve. In this course, you'll take a journey into the future of space exploration. You'll look at what is being designed and built right now, plans for what is next, and what you can expect to experience in the cocoon of low earth orbit (LEO). You'll also examine the aspirational goals across the space industry as humans become a truly spacefaring species at the cusp of interplanetary civilization. And importantly, you'll also see how the technologies developed for this next phase of the grand human endeavor will profoundly benefit and protect day-to-day life here at home. In this first episode, you'll begin by taking stock of what humanity wants to do in space and the pathway for achieving these objectives.

The Four Futures

The Four Futures model is a straightforward way of dividing the kinds of purposes that people will have in their activities in space. The future humanity is living now is one of exploring—going over the next hill, looking at what's there, learning about it, and bringing that knowledge back home. However, the future many space enthusiasts dream about is expanding the footprint of civilization out into the solar system.

The other two futures come into play because no amount of exploring can fund what it will cost to expand. So, a gap, a dilemma, and an economic challenge exist there. In this regard, the other two futures—experiencing and exploiting—are the best way to bridge from exploring to expanding.

Experiencing means people—average people, not highly trained, professional astronaut crews—flying in space for whatever purpose, primarily to experience what it's like there. Exploiting is about directly extracting value from what space offers for the terrestrial economy. The reason those two futures are the bridge is that they alone are able to tap sources of capital outside the top-line budget constraint of government-funded programs. They can reach into the pocketbooks of people who want to go themselves and experience space or the capital resources of entrepreneurs and investors who are expecting to make a profit from extracting value in space. Together, they will enable humanity to eventually bridge from merely exploring to fully expanding.

Star cluster MELOTTE 15

Traditionally, the only way to reach space was through government agencies or the military, but that paradigm has significantly changed. Now, the public-private partnerships that NASA instituted almost 10 years ago are starting to pay off. The private sector has always built, designed, flown, and launched spacecraft for NASA. However, in this new paradigm, while the government is still providing funding, it's moving at an accelerated pace with the industry partners, who are taking on much more responsibility. It really is a public-private partnership, which helps to significantly accelerate the pace of launches and access to space—which has always been a huge barrier.

Providing Access to Space

If the government is running the entire system, it tends to be much slower. But now, there is the pace and competition from industry, with many industry players involved. That's friendly competition. Most of these players are being funded by NASA, but they're also meeting their fixed-price contracts and getting a lot of launches up safely. Such access also opens things up for academia, where students now have access to and are flying their own science, technology, and payloads.

So, a relationship exists now between the government putting in the funding, the commercial teams coming to the table with ambitious goals to work with NASA, and then the field opening up to the scientific community and academia so that they can get the best technology flown for the future of space. This process is what is meant by democratizing space and providing access for all.

The Major Commercial Players

Who are the major players and commercial companies providing access to space? Even before one gets out to space, wonderful commercial opportunities exist to experience aspects of human spaceflight here on Earth. Zero-g parabolic flights, led by Zero Gravity Corporation in the United States, are one of the best tools. Essentially, these parabolic flights fly an arc in the sky, pitch steeply upward at 45°, nose over, and pitch very steeply downward at 45°;

they fly that arc 30 to 40 times in a flight. It's essentially a roller coaster in the sky that allows someone to get 20 to 30 seconds of sublime microgravity at the top of each of those arcs.

Blue Origin, which was founded by Jeff Bezos, looks at things like the New Shepard rocket—a suborbital platform that provides a chance to test research in a suborbital fashion in addition to an opportunity for space tourism. The company is also working on an even heavier lift rocket, a range of interesting concepts to take people within LEO and beyond, and a human landing system for returning to the Moon.

SpaceX, founded by Elon Musk, has pioneered a new road to space. For example, the Falcon 9 rocket, the Falcon Heavy rocket, and new and upcoming craft like Starship and the Super Heavy rocket will be able to send much greater mass to orbit in a much cheaper fashion. In addition, SpaceX's Dragon capsule provides resupply missions for the International Space Station (ISS), and the company is also working on a human landing system to return to the Moon.

Axiom Space has an interesting role in the space industry. Its approach to building its Free Flyer space station is to begin by adding modules to the existing ISS architecture and essentially expand off of the ISS. So, while the company is working on that interim plan, it's able to help researchers at MIT and Aurelia do payloads on the ISS and practice for its upcoming Free Flyer station as well.

Beyond Blue Origin, SpaceX, and Axiom Space, Voyager Space is developing a space station platform known as Starlab, Virgin Galactic has its space plane, and United Launch Alliance has pioneered an alternate road to space with capability such as the Atlas 5 and Delta Heavy 4. On top of all this, some new players in this active and burgeoning ecosystem include Vast, Gravitics, Gravity Lab, Max Space, Rocket Lab, Relativity, and Stoke Space.

All this demonstrates the immense growth and interest in the sector and the beginnings of a sustainable in-space economy. In this regard, space is not just a particular sector but also a domain where many, if not all, of Earth's businesses apply. It will see hospitality, entertainment, manufacturing, biotechnology, and material science—even in-space plumbing, welding, and trades jobs.

INTERNATIONAL SPACE STATION
orbiting Earth in space

Why Go to Space?

All of these different companies building infrastructure raise an important question: Why look to space when so many challenges on Earth still need solving? The first reason is exploration. The fundamental search for new knowledge is intrinsic to humanity and expanding people's horizons. As people go out and explore, they learn more about how to preserve their own civilization and about their own planet. Their ability to operate in the space domain and protect Earth from a range of dangers—from asteroid impacts to solar flares that could damage electronics—is also a critical aspect of their ability to sustain human civilization. In addition, the more people go out and learn about how to travel away from Earth, the more they come to appreciate the planet's fragility and beauty.

Beyond these lofty goals, there are more practical reasons to pursue space for technology spinouts and many other reasons. For example, the technologies and research being undertaken in space need to work in a vacuum, under extreme temperatures, and on a very dusty lunar surface that has incredibly erosive properties. So, if a piece of technology can work under all of those extreme conditions, then it's going to work on Earth in anything people can throw at it. In this regard, these technologies always have great applications on Earth.

In addition, such a scenario forces people to solve problems they might not even think of on Earth—or that they might not have to face yet. It pushes those boundaries and makes people think outside the box and about technologies and solutions in a very different way. It also forces them to come up with things they couldn't invest in on Earth because nobody's even thinking about them.

Examples abound of technologies that have been transferred from the space program to benefit our lives. In the Apollo era alone, we learned more about how to construct microwave ovens and invented Kevlar and quartz watches. In the ISS era, LASIK eye surgery has come out of some of the careful docking technology that's used to bring spacecraft together in orbit. We've even learned about machine learning, scientific instruments, and a range of biotechnology and other applications.

In addition to technology transfers, one has to consider the next-generation technology that is evolving and will come from the next wave of space habitats—from heating, ventilation, and air conditioning innovations and space-based solar power to growing retinas in orbit to restore vision. An amazing opportunity also exists to offload some of the hazardous operations that currently damage Earth (for example, mining and chemical byproduct manufacturing), move them into safe places in orbit where there's not an atmosphere that catches and traps pollutants, and ultimately restore Earth to a garden planet.

EARTHRISE taken by Apollo 8 crew member Bill Anders on December 24, 1968

2

To Boldly Go Again: Back to the Moon

MORE THAN 50 YEARS HAVE PASSED SINCE THE LAST Apollo astronauts walked on the Moon. Now, humanity is headed back, but this time, NASA will rely on commercial partnerships to achieve many of its goals. In this episode, you'll look at some of the different missions that will allow a new generation of astronauts to return to the Moon. You'll also explore how they plan to stay there and why the Moon is an important step in reaching humanity's next goal—a human-crewed mission to Mars.

Returning to the Moon

NASA's next-generation rocket, the Space Launch System (SLS), will be the platform that ferries astronauts to the Moon. It can send the Orion spacecraft, four astronauts, and cargo directly there. Ultimately, the SLS will be supplemented with a range of other rockets to help develop this road to space between Earth and the Moon.

Why go back to the Moon? In large part, returning is for scientific discovery. A sustainable lunar settlement will also help people learn about how to live for long periods in deep space and rekindle the spirit of space exploration. Finally, it will provide a proving ground for sending humans to the surface of Mars and beyond.

Having humans on the Moon in the coming years is important because experts need to look at the technology and the development of technology to ensure a safe future Mars mission. They also need to understand the life support systems they need to design and develop and the heavy-lift launch capability they need to get to the Moon and Mars.

When they go to the Moon, not only do they have to get into orbit of the Moon, but they also need a safe lunar lander. A few industry partners are working on that. Then, they can go to the Moon to get their science done and use it as a laboratory. The Moon has one-sixth gravity compared to one gravity on Earth, whereas Mars has three-eighths gravity. So, the Moon is a great proving ground for this idea.

Craters, hills, and valleys on THE MOON

When it comes to exploring the Moon, lava tubes exist underground. These tubes are also a great place to put human laboratories—and maybe even settlements—because people won't have to build all their structures and could literally live underground.

The above are some of the high-priority research, exploration, and technology goals that exist for going to the Moon and learning how to live there. It's the next logical step—the Moon will prepare people for the difficulty of getting humans to Mars.

Project Artemis and the Moon's South Pole

Astronauts are going back to the Moon through Project Artemis. Up to three Artemis missions are already planned, with Artemis IV and V very much in the works. Artemis I—an uncrewed test of the SLS and Orion spacecraft around the Moon—was completed in 2022.

Artemis II comprises a 10-day human-crewed test of the SLS and Orion spacecraft orbiting around the Moon and is planned for September 2025. Astronauts Christina Koch and Victor Glover have already been selected to circumnavigate the Moon.

Looking forward to Artemis III and beyond, the first woman and person of color to walk on the lunar surface will be on these missions, targeted for some time between 2026 and 2028. Their mission objectives are to land in a new area, explore, and perform science experiments at the Moon's South Pole, which has many areas that are permanently shaded. These regions are most likely to contain water ice. Using electrolysis, scientists can separate water into its hydrogen and oxygen molecules, which can be used as fuel for rockets and eventually deep space exploration. If this water ice can be leveraged, the Moon could therefore become a gateway—a fueling depot—for the rest of the solar system.

ARTEMIS II crew

The South Pole also contains mineral resources and certain rare Earth materials that humanity treasures. For example, helium-3—quite rare on the surface of Earth but abundant on the Moon—could be used one day to power fusion reactors on Earth. In addition, medical technologies for MRIs use helium-3, which is also highly useful for the super cooling that needs to be done for quantum computing and fusion reactors.

NASA's Commercial Lunar Payload Services Initiative and Lunar Gateway

What is the plan to accomplish the aim of returning to the Moon? NASA's Commercial Lunar Payload Services (CLPS) program has the idea of essentially contracting with American companies to deliver payloads to

cislunar space for NASA. For Project Artemis, these CLPS partners will perform scientific experiments, test critical technologies, and ultimately demonstrate capabilities on the lunar surface, such as landing their own spacecraft and developing their own rovers. These endeavors are all part of a way of creating a sustainable lunar settlement on the Moon. The way forward is to send robots, collect data, and test technologies that would be important in future missions—supporting the human infrastructure that would come later.

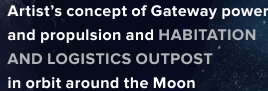
Soon, a taxi service will exist between Earth and the Moon. The first mission from the company Lunar Outpost—named the Mobile Autonomous Prospecting Platform (MAPP-1) mission—will carry two experiments affiliated with MIT's Space Exploration Initiative and To the Moon to Stay mission. The first is the AstroAnt, an autonomous swarm robotics platform whose objective is to collect critical data on the exterior surfaces of spacecraft for diagnosis and repair. The aim of the second experiment on the MAPP-1 mission—named RESOURCE, for Resource Exploration and Science of OUR Cosmic Environment—is to capture high-resolution 3D imagery of the Moon's surface.

Amazing work like these experiments—along with many other CLPS initiatives—will give people the data they need to return humans to the lunar surface. But what is the plan for gaining a permanent foothold on the Moon? It all starts with a permanent presence in lunar orbit called Lunar Gateway.

Lunar Gateway will be built with international and commercial partners. It is an integral component not only for returning to the Moon but also for future missions to Mars and beyond. Beginning with Artemis IV, astronauts will use the Habitation and Logistics Outpost (HALO)—the central hub of a gateway station Northrop Grumman is building—as an orbiting home around the Moon. Later missions will also use the International HABitation module (I-HAB), which the European Space Agency is building. Together, the HALO and I-HAB modules will keep astronauts healthy and thriving for up to 30 days.

This new space station also offers larger room for conducting science, eating, exercising, and resting. Unlike the ISS in LEO, Lunar Gateway will be seasonal, which means that the astronauts may not be continuously operating the station. It must incorporate novel technology with regard to artificial

intelligence (AI), AI agents, and autonomous operation to be able to sustain itself between the periods when it's crewed by astronauts.



Artist's concept of Gateway power and propulsion and HABITATION AND LOGISTICS OUTPOST in orbit around the Moon

Humans on the Moon

Lunar Gateway will ensure a sustained presence on the Moon and a platform for transporting astronauts down to the lunar surface. The next part of NASA's plan involves the Human Landing System (HLS). Crews will board the HLS from either the Orion capsule or Gateway, and SpaceX intends to perform at least one uncrewed mission prior to the Artemis III lunar landing.

Once people are there, the plan isn't just to simply visit the Moon but to establish a permanent lunar home. However, a lot needs to be done to make that happen. In this regard, over the last several decades, NASA and other space agencies have been very interested in additive manufacturing or 3D printing as a construction technology to support the creation of surface habitats—as well as other infrastructure on the surface of the Moon and Mars. NASA is interested in this technology because it enables autonomous construction of these structures in advance of a human crew's arrival to the surface, which will be essential for mission success and ensure that astronauts have a safe, robust, and durable place to live and conduct experiments.

The premise is basically that a robotic constructor or builder deploys on the surface of the Moon or Mars and uses the local and indigenous materials of the planet as construction feedstock and material to assemble and fabricate a habitat or some other civil engineering–type structure. More often than not, these are horizontal structures like roadways and landing pads and various kinds of vertical structures—for example, unpressurized hangars and garages. Eventually, there will be the challenge of pressurizing a habitat certified for human occupancy.

Landing pads are essential for future infrastructural development on the Moon. When astronauts land in the same spot in a repeated area on the Moon, they create massive craters in that landing area. In addition, the ejecta from the landing impact forces particles into orbit around the Moon, so it's harmful to surrounding hardware and to humans. A landing pad would enable astronauts to land and launch from the same sites repeatedly and mitigate such risks.

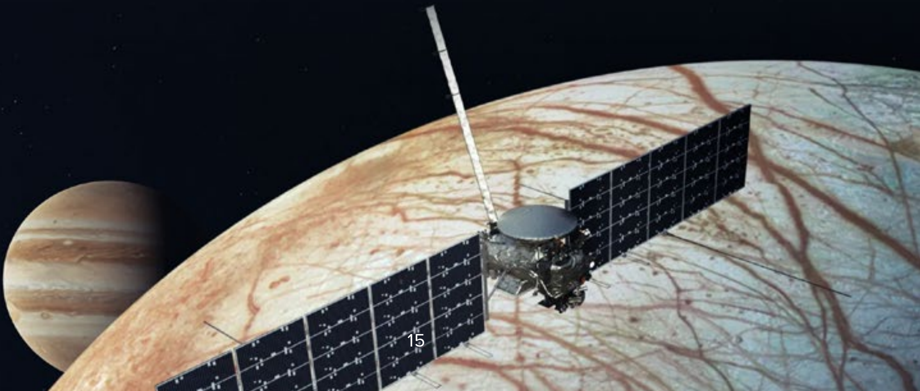
Considering all of this information means that humans will be not only landing on the Moon this decade but also building a space station in lunar orbit, along with critical infrastructure and a permanent base on the surface. The challenges will be significant, and there are sure to be some setbacks along the way. However, the path to success is clear, and some of Earth's best minds are working on this exciting project to make the Moon part of humanity's home-world ecosystem.

The knowledge and technology people gain from exploring and living on the Moon will help humanity here on Earth—from preserving food to developing robust life support systems—and will also give us the tools needed to extend our reach millions of miles deeper into the solar system and on to our next destination: Mars.

3

Dare Mighty Things: Destination Mars

AS SCIENTISTS WORK TO ESTABLISH A PERMANENT SPACE station in orbit around the Moon and a base on the lunar surface, they'll use what they learn to reach a long-imagined goal: having humans visit and eventually live on Mars. Visible in the night sky, Mars has loomed large in humanity's imagination for millennia. In this episode, you'll explore the many real-life scientific challenges of landing on and inhabiting the Red Planet, what scientists will need to do to overcome each of them, and what it'll take to ensure humans can thrive once they're there.



Landing on Mars

The first obstacle to overcome to land humans on Mars is mission duration. A crewed mission to Mars would take up to 3 years in total—6 to 9 months to get there, a stay of around 12 to 18 months while Earth and Mars align again, and another 6 to 9 months for the return home. In addition, given such a duration, a rescue mission for Mars would be unrealistic, profoundly shaping the dynamic for safety and redundancy in mission architectures, in resupply and logistics, and for supply chains in general for Mars missions. So, any crewed vehicle to Mars would need to be large enough to carry the supplies to last for the entire trip—unless there had been early pre-trip planning where resources were delivered ahead of the crew.

Mars is about one-half the size of Earth by diameter and between one-third and three-eighths the gravity of Earth—and it also has a very light atmosphere, with much less drag to slow down incoming objects. These two aspects combined mean that the descent trajectory to the surface of Mars would be quite different from that to Earth.

Instead of landing an entire ship on the planet, an alternative would be to use an Apollo-inspired Mars excursion module that would combine a crewed descent/ascent vehicle with a small surface habitat for brief stays on the surface. New entry, descent, and landing (EDL) technologies—for example, using separate descent, surface habitat, and ascent vehicles—are currently being designed to address these challenges.

Illustration of NASA'S PERSEVERANCE ROVER landing safely on Mars

The Many Challenges of Mars

Once all of the technical challenges to landing humans on Mars had been solved, even existing on Mars for up to 18 months would introduce new challenges of its own. The first is distance. Because Earth and Mars orbit at different rates around the Sun, Mars's distance from Earth ranges from around 35 million miles to up to 250 million miles, with an average distance of around 140 million miles. Because of the separation between Earth and Mars, it can take between 5 and 24 minutes for a communication signal to travel between Earth and an astronaut on Mars—and that's just one direction. The aim here is to develop a range of different virtual reality, AI, and other communication technologies to address this gap.

The next challenge is radiation. Without an iron core like Earth's, Mars has no global magnetosphere. What this means is that it doesn't have that same protective buffer, so the surface of Mars garners much more significant radiation from the Sun and from cosmic background radiation—and that reaches the surface. This radiation would be harmful to humans and any exposed organic materials. Therefore, with regard to long-term habitation—even for just an outpost—people would probably need to live underground or in some type of heavily shielded space habitat.

Another challenge resides in Mars's atmosphere, which is predominantly carbon dioxide, so it's not breathable for humans. In addition, the atmosphere is extremely thin, with surface pressures that are less than 1% of sea-level pressure on Earth. As such, pressurized extravehicular activity (EVA) suits would be required anytime someone leaves a habitat.

Ultimately, with all of these different challenges in the background, even deciding where to land a crew on the surface is critical. Sites near lava tubes on Mars could be used for underground habitats that would offer protection from radiation. Sites near usable water ice are also very compelling because the water could be used to make fuel for the return journey to Earth and potentially as a radiation-protective layer for space habitats.

Even before people get there and face these challenges, there's the toll that simply being in microgravity will have had on the human body during the long trip to Mars. To address this, scientists will need to develop

a countermeasure of artificial gravity for the trip to Mars so that the astronauts can arrive on Mars with better strength. Finally, while it's a positive that Mars has around three-eighths of Earth's gravity, human crews will probably still need some assistance acclimating to the Martian environment—perhaps through some kind of exoskeleton support or robotic assistance as they recalibrate to a new gravity environment.

Living on Mars

For humans to live in the extreme environment on Mars for up to 18 months, they will need to grow at least some of their own food to be able to bring fresh nutrients into the mix. Unfortunately, Mars has perchlorates in its regolith, or what is called soil here on Earth. And there are advantages and disadvantages to this.

The first advantage is that perchlorates can absorb water out of the Martian atmosphere when heated to around 200°C—so they're a good source of being able to extract that water. And even more interesting, when heated to between 200°C and 500°C, they release a significant amount of oxygen. So, it's very plausible that scientists might be able to harness perchlorates as part of a life support system for water or oxygen in the future.

Unfortunately, perchlorates are toxic to humans, and therefore, people wouldn't want to grow food natively in the Martian regolith within that perchlorate high-concentration area. Entirely self-contained greenhouses would most likely be necessary to be able to grow enough throughput of food to feed a crew, which would take new technology that is able to function in a long-term, steady-state fashion and produce safe food within a self-contained, captured atmosphere and environment.

As for the structures that crews could potentially live in on Mars, any habitat is going to need to be pressured while also protecting inhabitants from high radiation and extreme cold. It would need to be able to get that gas mix correct so that someone is breathing air that is compatible with human life on the inside of their habitat. At first, short-term habitats could be used, and then—as humans establish a longer-term footprint on Mars—more robust structures would be needed.

Scientists are fascinated by the possibility of using water ice as a building construction material. They have realized that the true value add in doing so is that it's superior in shielding astronauts against galactic cosmic rays and solar particle events over aluminum or the standard construction material for 3D printing—regolith. They have envisioned an ice habitat as a glowing beacon on the surface of the planet and imagined that the water ice could introduce a connection between the astronauts and their broader landscape—which other opaque materials would likely not be able to do. Since such a Mars ice house is deemed to depart very radically from the expected solutions for habitats to be constructed out of regolith, designers have also come up with a Mars X-House, which is a sulfur-based regolith habitat.

MARS X-HOUSE
design concept

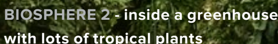
Other construction technologies are being considered, some of which have to do with deployable habitat sites, such as inflatable structures, while others are pre-integrated, hard-shell units that are manufactured on Earth and then launched into space. And there's no reason to believe that any one of these construction systems would need to operate independently of one another—they could work together.

Mars Time Frame and Technologies

When is NASA's target for landing a crewed mission on the surface of Mars? The goal is to have boots on the ground in the late 2030s. That time might seem far off, but lots of work is still needed between now and then on everything from EDL technologies and agriculture to the design of space habitats and understanding what the science mission would be. The first thing is to return humans to the Moon, as the Moon will serve as a proving ground for many of the technologies that will be needed for Mars.

Some very special Mars-specific technologies could include advanced propulsion systems: How can scientists speed up the journey, especially when the planets are farther apart? Are there opportunities to explore things beyond just the chemical propulsion that currently powers most rockets? Would they consider nuclear propulsion that will get people there faster and more efficiently?

Inflatable landing gear is another consideration—to be able to deliver those heavier


BIOSPHERE 2 - inside a greenhouse with lots of tropical plants

vehicles to the surface—or generally trying to understand the promise of different types of EDL technologies. And people will need next-generation EVA suits that are tuned to the particular Martian environment. They will need profoundly better sustainable agriculture, at a larger scale, with a biosphere-like environment. They'll also want to be able to have mobile habitats and lab spaces—rovers to be able to expand their reach beyond just the initial settlement area on Mars and on the Martian surface.

Two final things to keep in mind are next-generation power generation—so that systems can operate regardless of location or weather—and laser communication systems that can send more data at a time. These technologies would be critical to moving into this new architecture for living on Mars and communicating back to Earth.

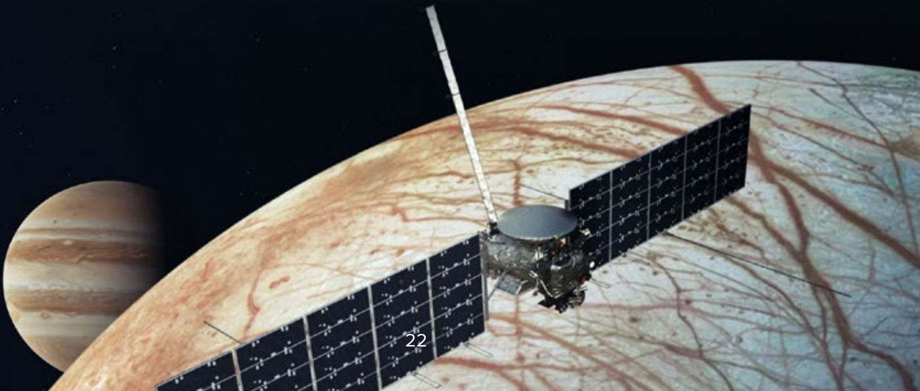
Importantly, Mars would likely only be an outpost for a long time to come—something like McMurdo Station in Antarctica—and perhaps not so much a place to build a civilization. The reason for this is that Mars is around three-eighths the gravity of Earth, which means that it's unclear whether a fetus would be able to be brought to term. A lot of science would have to be done to understand whether a woman can incubate a baby within this environment and have it still be able to lead a normal life in the way that one thinks of on Earth.

Landing humans on Mars won't be easy, and significant challenges need to be overcome. But humans have done the impossible before. How many people thought that landing men on the Moon was a pipe dream? Yet NASA was able to accomplish that feat in just over 8 years of sustained effort after the very first human, Yuri Gagarin, ever flew to space. And NASA managed all of these feats with computers and technology far simpler than what exists in iPhones. Imagine what they could do today, now that NASA has unleashed the innovation of private industry with its commercial partnership programs.

4

The Future of Living in Space

DISTINCT FROM SURFACE HABITATS, SPACE STATIONS are typically floating platforms in orbit around another celestial body, like Earth, the Moon, or Mars. From the pioneering days of Salyut and Skylab to the engineering marvels of the ISS and China's Tiangong, space stations have become sophisticated laboratories that test new limits of scientific and human capabilities. In this episode, you'll look at how the requirements for living aboard space stations are changing and what you can expect to see in LEO, around the Moon, and on Mars in the near future—which will open up entirely new opportunities for living, commuting, working, and playing in microgravity.



Space Stations and the ISS

The first early space stations—for example, the Salyut space station program, launched by the Soviet Union in 1971, and the Skylab space station, launched by the United States in 1973—were single-module designs. They were basically just one core module, meaning that they consisted of a simple containment without any expansion, often for a very small crew.

After Salyut and Skylab, the next space stations were multi-modular designs, meaning that expansion modules connect to a core segment to increase the living and working space. The Mir space station—operated by the Soviet Union and later by Russia from 1986 until 2001—was a huge sea change in the space industry. It went from relatively small, modest space stations to a large, multi-unit, successful research platform that featured a great deal of international collaboration. And it's a model that was then inherited and grew into the ISS, which began in 1998 with collaboration from many different space agencies. The station was therefore an incredible feat of both engineering and multilateral international cooperation.

What's remarkable about the ISS is that it has been continuously occupied since 2000. However, rather than prolonging the life of the ISS indefinitely, NASA is incentivizing the development of commercial space stations, which will finally allow the ISS to be decommissioned. The anticipated timeline for that is early 2030.

In addition to the ISS, China launched the Tiangong space station—Sky Palace or Heavenly Palace—core module in 2021, followed by two additional modules in 2022. The US-led ISS and Chinese-led Tiangong space stations are the current key space stations in orbit, soon to be joined by a range of different commercial endeavors.

The planned decommissioning of the ISS in or around 2030, coupled with the rapid growth of the commercial space sector, has ensured that the next generation of space stations will even further advance the previous capabilities. Still typically modular in design, the new space stations will take advantage of novel technologies, but they will also need to address new requirements for living and working in space and be able to accommodate an entirely new type

SKYLAB SPACE STATION CLUSTER in Earth orbit

of audience—members of the public who are flying to space for the first time without necessarily having been trained like the fighter pilots of old or the top amazing talent that one typically sees with an astronaut.

The Next Generation of Space Stations

When humans first started flying in space in the early 1960s, they were passengers in the truest sense—hero passengers—because those systems were rather rickety, with very slim margins. And as things progressed—through the Apollo program, Skylab, Mir, and the shuttle and space station era—people became better at engineering systems that were more efficient, reliable, and capable.

Such systems are still designed almost exclusively by engineers, which makes sense as the facilities flown in space are laboratories. Therefore, most of what goes into a terrestrial laboratory is engineering because of the services one has to provide and the requirements they're trying to meet. As the demographics of spacefarers evolve and comprise more visitors and more diverse types of workers, the requirements for space architecture will also evolve. Such a situation will lead to types of architecture that engineers do not build in or for space today, including amenities for high-paying tourists or people who are living in space for part of the year. For example, they will need to be able to provide—and therefore design for—cooking, gymnasiums, and large areas in which groups of people can assemble for social or even safety purposes.

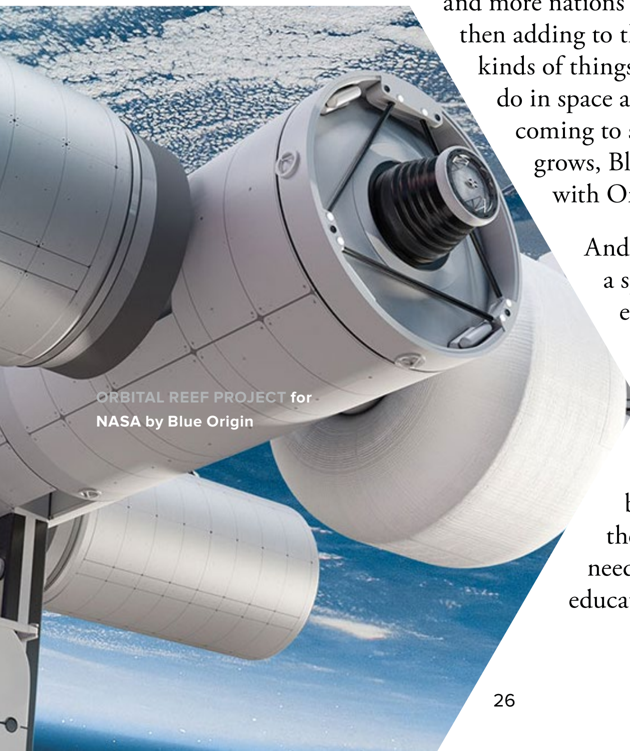
In progressing through this spectrum, the number of explorers becomes a small fraction of the number of spacefarers. More spacefarers are workers who are paid to be there or visitors who are paying to be there. The requirements will diversify, and the need for a more traditional type of design for human environments will start to come to the fore. Three key companies—Blue Origin, Axiom Space, and Voyager Space—are building space stations with these new requirements in mind.

Orbital Reef

Orbital Reef is a next-generation, multi-user space station that will pick up where the ISS is leaving off at the end of this decade. Blue Origin built this space station, so it's not run by governments—it's run commercially. As a result, Blue Origin can open it up to the entire world to come and join them—they can use it for science and technology but also for the next generation of commerce and for things like tourism, filming movies, doing arts, and educating students.

What's most exciting about Orbital Reef is that it is scalable. It starts with a core that has all the infrastructure one might need—all the power and thermal controls and communications—and the company can add modules onto the sides and keep expanding as the demand grows.

This idea is interesting when thinking about growing the space economy, starting with space agencies from around the world and growing so that more and more nations are coming into space—then adding to that space industry the kinds of things a company might want to do in space and the individuals who are coming to space. So, as the market grows, Blue Origin can grow with it with Orbital Reef.

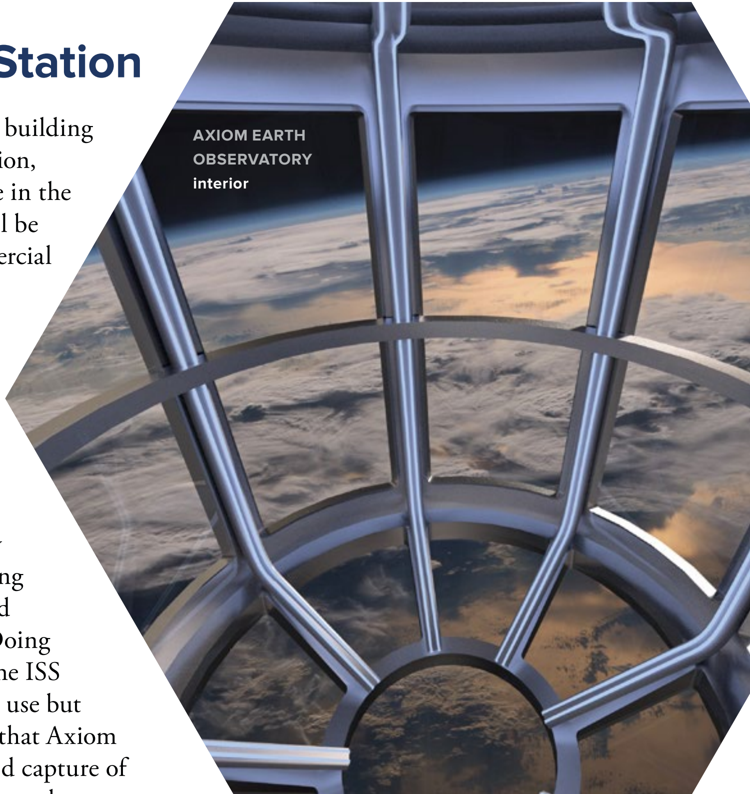


ORBITAL REEF PROJECT for NASA by Blue Origin

And Orbital Reef is not just a space station—it's an end-to-end service. Blue Origin is also considering the next-generation transportation that gets one there, the transportation that brings one home, and all the ground services one needs to support the research, education, and business creation

being done up in LEO. The idea is to expand all the things people do on Earth so that they can now go out into space—and space becomes part of their ecosystem.

Axiom Station



Axiom Space is building the Axiom Station, which is unique in the sense that it will be the only commercial space station to attach to the ISS. After attaching its first module, the company will be able to turn the lights on immediately and start running experiments and hosting crew. Doing so will enable the ISS to maximize its use but also make sure that Axiom Space has a good capture of existing markets and customers along the way. One of the existing markets is flying people to space. Axiom Space is hoping that with commercial platforms, it can encourage the emergence of new players into the space marketplace.

Research has been carried out on the ISS for many years, and Axiom Space hopes that its platform will continue that history and expand it to additional countries and companies that want to do work in space. Of the emerging

markets that are enabled by commercial platforms, the most important is in-space manufacturing—using the microgravity and the space platform to make things in space that one can't make on Earth.

Another use for the Axiom Station is as a testbed for logistics and infrastructure technologies—for example, satellite servicing, debris recovery, and using the space station as an orbital data center. Those kinds of services are important and emerging as the ecosystem grows and more spacecraft get into space.

So, a space station is a multi-use platform that acts as a hotel and training facility for people. It's a laboratory for research. It's a factory floor for manufacturing, and it's a testbed for new technologies in orbit.

Axiom Station will also host the Earth Observatory—the largest window ever built in space. It will have multiple 4-by-8-foot windowpanes providing a 360°-view of Earth that will be on the underside of the space station so that any crew that enters it can get unparalleled views of the planet.

STARLAB
in low Earth orbit

Starlab

Voyager Space is constructing Starlab, one of the three contracts awarded by NASA to build the replacement for the ISS. One area of focus is antimicrobial and self-cleaning technologies, which are very important in the context of space and space stations. Because astronaut time is absolutely critical, Voyager Space wants its astronauts to spend time on research and development and running experiments to benefit life on Earth—not necessarily on maintaining the station.

Another important part of Starlab is that it's 8 meters in diameter, which is quite a bit different than the 4.2 meters of the ISS modules. Since this is space and it's all about volume, 8 meters is not twice as big as 4.2 meters—it's three times as big because there are the X, Y, and Z axes in space given that there's no gravity.

Until the next-generation rockets were feasible—namely SpaceX's Starship, which has a much larger rocket fairing—everything was limited to the existing rocket fairing size. And that factor limited the diameter of the space station modules to 4.2 meters. Now, with the next-generation rockets, Voyager Space can do the 8-meter volume, build the entire space station on the ground, and send it to orbit in a single launch. This concept is very different from the ISS, which was constructed over time through many launches.

As space stations such as Orbital Reef, Axiom Station, and Starlab become realities in LEO—and maybe many other space stations to come—they not only push the boundaries of engineering and design innovation but also challenge people to reimagine life beyond Earth's confines as a place to live, work, and play in microgravity.

This new era of space habitation also holds the promise of enhancing people's capabilities for exploration while enriching the potential for multinational and commercial collaborations—opportunities that will benefit humanity both on and off world.

5

Next-Generation Space Stations

How can engineers build space structures larger than the largest rocket payload fairings? How can they build the next generation of space stations that will scale to be able to house not just the dozen or so people in orbit currently but hundreds if not thousands of people? In this episode, you'll focus on a type of space architecture that the Aurelia Institute is designing and testing called the TESSERAE. It is modular, self-assembling, reconfigurable, and inspired by self-assembly in nature, with the goal of building orbital space stations—and perhaps even ultimately cities in space—that are worthy of science fiction.

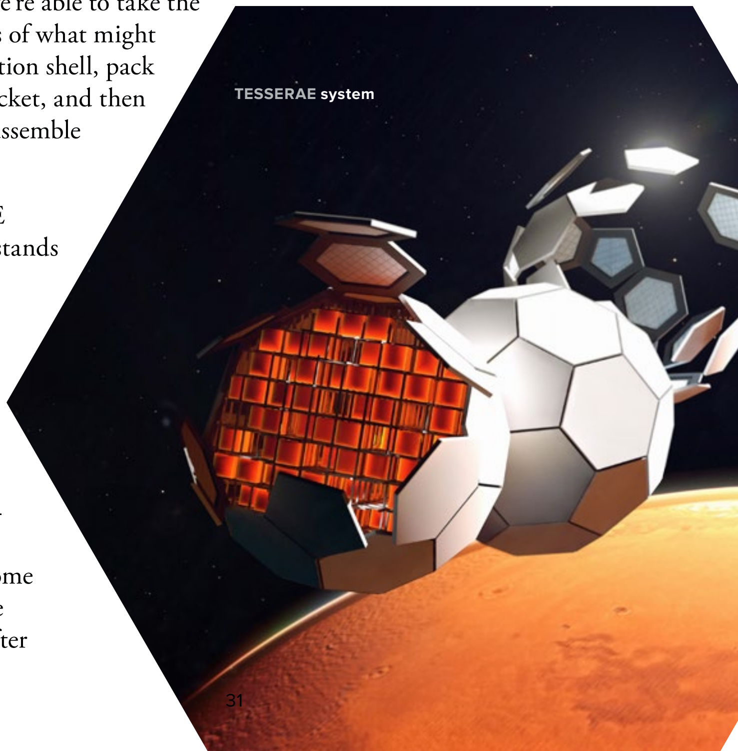
The TESSERAE System

Traditional space station design relies upon a modular configuration. A core module is sent into space in one prefabricated piece—typically an aluminum shell—followed by additional segments until enough of a habitat exists to accomplish mission goals. These types of structures are proven and reliable and have allowed people to live and perform research in space for decades.

However, if humans are truly going to become a spacefaring species—extending humanity's reach from LOE to the Moon, Mars, and beyond—we'll need to think differently and invent technology to scale structures and build larger structures in space with minimal human intervention.

So, how do engineers build these massive-scale structures? First, a new paradigm needs to be created. Drawing from how self-assembly happens in nature—for example, with ants self-assembling to form amazing bridges that can span spaces far bigger than their own bodies—allows us to imagine a future where we're able to take the constituent parts of what might make a space station shell, pack them flat in a rocket, and then deploy and self-assemble them in space.

The TESSERAE system—which stands for Tessellated Electromagnetic Space Structures for the Exploration of Reconfigurable Adaptive Environments—uses small tiles that dock and come together to make a bigger shape after


TESSERAE system

they've been released from a rocket. When the tiles are swirling around and free-floating in space, they sometimes come together perfectly using magnets on their edges. But sometimes, the tiles will come together incorrectly, and therefore, the ability to do autonomous live error detection and correction is designed into the system. After all of the tiles that form a TESSERAE buckyball—that's the particular shape—have come together, a series of clamps will knit the structure together for pressurization to make sure it can withstand the force due to air pressure.

One of the special components of the TESSERAE technology around this notion of reconfigurability is that once these tiles have self-assembled into the buckyball, in addition to having them hold that shape, people can pop the tiles on and off. In addition to agile reconfigurability for changing mission needs, this also supplies the opportunity to have better control over maintenance of the station.

A TESSERAE structure can be as small or as large as one needs it to be. It can therefore be a small extra module—a storage space on a space station, for example—or up to as large as 10 meters in diameter.

Testing the TESSERAE System

Projects like TESSERAE don't just come to life from the moment someone has the idea and then go straight to deployment with humans in orbit. They undergo a series of iterative testing and steps to get them ready for this type of undertaking. One of the key milestones in the Aurelia Institute's development of TESSERAE was sending small miniature mockups of the TESSERAE tiles with all of the technology embedded up to the ISS.

From such a deployment, the Aurelia Institute could watch the tiles pirouette together. As they were floating through space, the company learned a lot more about the dynamics of how they will self-assemble and also about the timescale of how long it would take to self-assemble an entire ball in orbit.

Even before getting to the ISS, the Aurelia Institute has also done years of zero-g flights to test TESSERAE and the prototypes in the reality of weightlessness. And in the future, as the company builds toward human-

TESSERAE
habitat illustration

scale, space-grade tiles for the actual technology demonstration mission in orbit with humans, it will take all of these learnings from these multiple different deployments to get ready for the final TESSERAE deployment at human scale.

However, for TESSERAE to be a compelling vision in the longer term, the Aurelia Institute needs more than just the engineering and science of these prototypes and tiles to work. It also needs to think about thoughtful interior design and architectural considerations that are user centered to create a fantastic and an enlightening life in space. Overall, the TESSERAE habitat concept comes out of a humanist vision that unites engineering and science with art and design—and, fundamentally, an aspirational philosophy of collective human living in space.

Long before humans will have the luxury of private homes in space, they will have groups of people commuting, living, and working together in a long tradition of small village life. And so, when the Aurelia Institute works on the TESSERAE technology, it works not only on the magnets and all of the engineering but also on designing the social structure, governance, and policy that also goes into the future of life in space.

Building the TESSERAE Pavilion

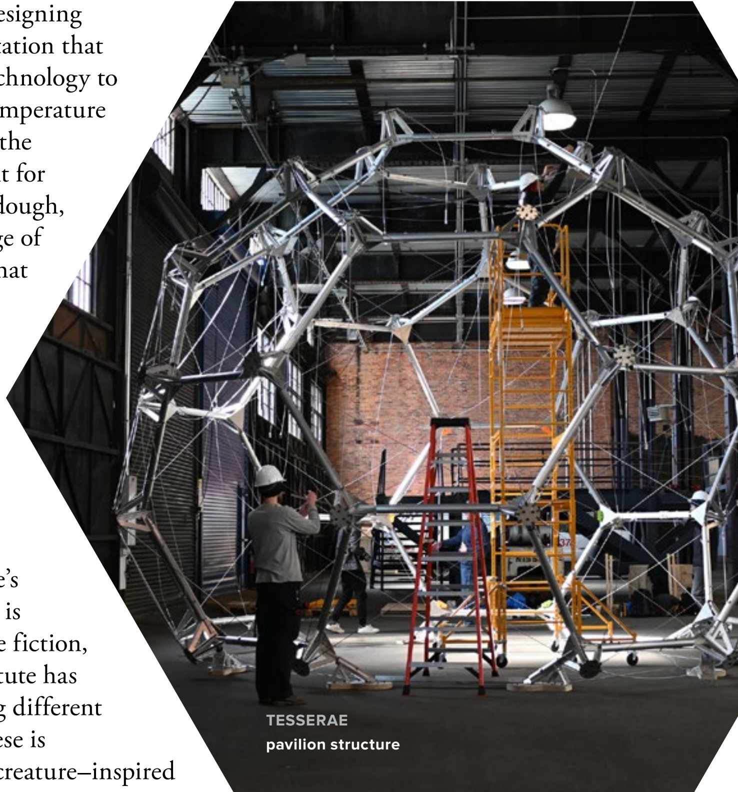
How is the Aurelia Institute bridging the gap from a small-scale set of prototypes with the self-assembling tiles to the ultimate space-grade version that will be extremely large and at a very different scale? To start, the company has to develop the core architectural concept. To be able to do that, it has built a life-scale pavilion—called the TESSERAE Pavilion—at the Autodesk Technology Center in Boston. This real-life creation is meant to mimic what will ultimately be the TESSERAE space habitat in orbit.

The reason the Aurelia Institute is doing it on the ground as a mockup first is twofold. The first reason is that it might take 5, 7, or even 10 years for a real habitat to be able to be ready for life in space, out there in orbit. And throughout all of that time, the company needs a platform where it can iteratively test and develop the technologies it is creating for the inside of the space habitat—all of the artifacts that would make it a life worth living in space.

The second reason is that the company can share it with the public. The idea behind the TESSERAE Pavilion is that while the Aurelia Institute is working in the background on the real space-grade tech, it has an example of exactly what life in space might look like in the future—a next-generation approach that can get people excited—and can show it to the public and walk them through it.

In creating the TESSERAE Pavilion, the Aurelia Institute is focused on the theme of growing, cooking, and eating in outer space. So, it'll need new technologies that will support these activities in microgravity, and one of the things the company is looking at is what it calls the Green Vault—a platform where people will be able to spray the roots of plants with water. In addition,

the institute is designing a fermentation station that will use water technology to filter a certain temperature of water to keep the temperature right for fermenting sourdough, pickles, or a range of different foods that will improve the experience of eating in orbit.



TESSERAE
pavilion structure

Finally, with regard to designing an interior environment that captures one's imagination and is worthy of science fiction, the Aurelia Institute has been prototyping different ideas. One of these is essentially a sea creature–inspired couch in zero-g, which allows a human—when floating through a space habitat—to come and nestle in with the structure and have the sense of comfort and care that people associate with their favorite places at home.

Fundamentally, what's so exciting for the Aurelia Institute about the TESSERAE architecture is that even if the company does a lot of custom outfitting in the end for the inside, the exoshell of the outside comes together remarkably quickly. Importantly, it comes together without astronauts having to do EVAs in orbit, where they put on a suit and risk their lives to go outside the space station and assemble things. The company is sparing them from

that because these tiles assemble on their own autonomously. Overall, the advantage of TESSERAE is this decentralized, agentless structure for the assembly of large-scale pieces and structures in space.

Beyond TESSERAE

The Aurelia Institute is also doing what's called a Space Architecture Trade Study—a literature review of more than 100 different space habitat concepts. It is basically trying to make sure it doesn't reinvent the wheel and that it is finding patterns and novel ideas that might be buried in decades of great work from NASA and other creative firms that have been thinking about the future of life in space and space architecture for a long time.

Then, out of what it learns from this review of all of the existing ideas about space habitation, the Aurelia Institute is doing a series of case studies on new concepts related to modular self-assembly—like TESSERAE—and spinning space stations for artificial gravity. Spinning a space station results in a centripetal force that essentially provides a sensation of gravity around the outer ring, depending on how big the ring is and how fast the space station spins.

Then, in the future, the company could perhaps work on huge space city concepts made out of polylithic, multiple rock—different pieces coming together for multi-module docking of a large conglomerate, resulting in a large amalgamation of space modules for a city.

All of this effort within the Space Architecture Trade Study is public work, and the Aurelia Institute makes sure to release it. As the company builds these concepts, it also wants to be educating the general public and bringing more people into the potential to be space designers and engage with all of the amazing knowledge the industry has amassed over the last few decades.

6

Life Support and Futuristic Space Suit Designs

AS HUMANS VENTURE FURTHER FROM EARTH, THE NEED for advanced technology to sustain human life in the harsh environment of space becomes ever more important. In this episode, you'll shift your focus to the critical technologies that ensure the survival and well-being of astronauts and future members of the public flying to space. From radiation protection and advanced life support systems to state-of-the-art space suits that provide better mobility and safety during activities both inside and outside of a space station, you'll see what will be possible in space and learn about the technology transfers that can help humanity here on Earth.

Radiation

Of the many various hazards to confront in space, radiation is among the most important to overcome. Radiation is largely managed in LEO because of Earth's magnetic field, but it will be a key challenge as people travel farther away from Earth—outside of the magnetosphere—and as they travel out for longer periods of time.

The biological dangers of radiation in space are significant, with the key issue being long-term damage to DNA and cellular repair mechanisms. Unfortunately, the total amount of inbound radiation over the type of a long-term career that's often experienced by NASA astronauts can materially increase cancer risk. It's something that's extremely important and that the space industry takes quite seriously around designing countermeasures to mitigate and reduce that risk.

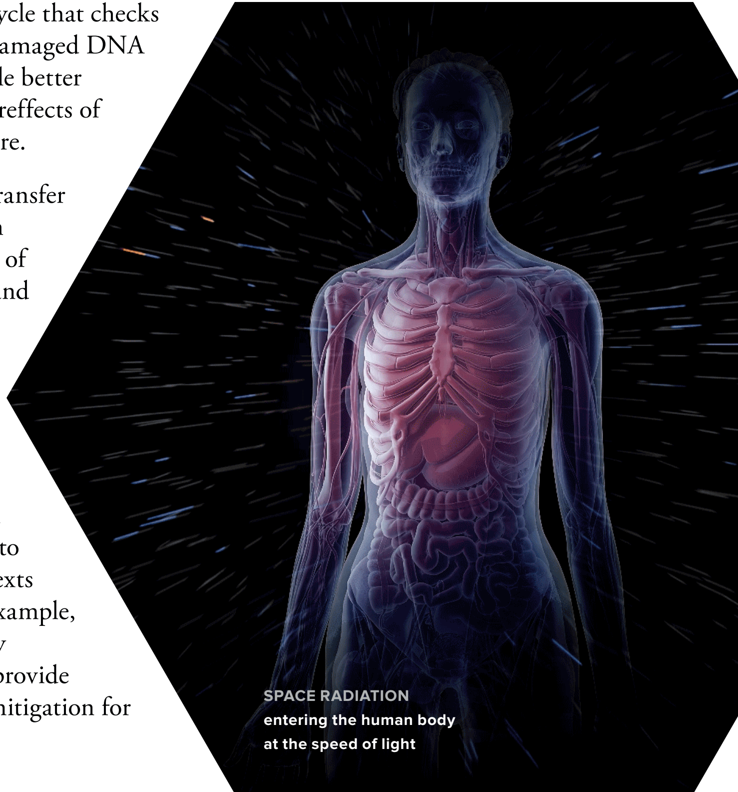
Different technologies can help shield humans from radiation. While lead is one of the best material shields for radiation, the depth of lead that would be required for shielding the space station would be incredibly expensive to get into orbit. An alternative would be something like hydrogen-rich polyethylenes—a certain type of plastic that is used on the Space Shuttle and the ISS.

Other research is looking to the ability of certain bacteria and fungi—living organisms—to find ways to survive in high-radiation environments like space. In some cases, such organisms form pigments that may play a key role in providing radiation resistance, which could be adapted to protect humans in space, particularly in relation to long-term exploration and spaceflight missions. Pigments may also provide insights into new materials or functions for promoting human health in space and take some of these learnings back to the surface of Earth, where people still contend with certain sources of radiation.

Another mitigation to radiation is the concept of water walls, in which an opportunity exists to use water as a protective layer in space stations—maybe eventually even a water layer in space suits and other types of habitats. In addition to this, radioprotectant drugs that promote faster recovery from radiation damage by stimulating the growth of stem cells or lengthening the

step in the cell cycle that checks for and repairs damaged DNA might help people better mitigate the aftereffects of radiation exposure.

Crossover tech transfer to cancer care on Earth comes out of these products, and it's an amazing opportunity to take some of the learnings from the rigors of designing for protecting life in deep space back to these other contexts on Earth—for example, radiation therapy that might also provide protection and mitigation for human cells.



SPACE RADIATION entering the human body at the speed of light

Life Support Systems

Just as important as shielding humans from radiation is the interesting challenge of keeping them alive in a special, controlled environment. Humans have evolved in a particular atmosphere, with a particular gas mixture and particular needs for temperature and humidity. Essentially, what is needed in space is to completely recreate that environment from scratch using an environmental control and life support system (ECLSS)—everything from

water recovery and conditioning the air so that it has the humidity and temperature required for a comfortable atmosphere to removing smells and other pollutants that accumulate over time and generating breathable oxygen.

A highlight here is direct air carbon capture, which is something people are keenly interested about on Earth in the face of climate change: How are we taking carbon dioxide out of the air? As it turns out, one of the things that's done quite well in a space station is to take carbon dioxide out of the air and turn it back into oxygen.

In addition to direct air carbon capture, a need exists for energy-efficient air-conditioning and air filtration. The combination of these three technologies—direct air carbon capture, energy-efficient air-conditioning, and air filtration—is critical to the growing construction market on Earth. So, again, experts are able to take some of these learnings from the development of space and bring them back down as good candidates for technology transfer on Earth.

Next-Generation Intravehicular Activity Space Suits

With regard to intravehicular activity (IVA) suits—space suits for inside space stations—a lot of active research is going into updating what the historical space suits have looked like. The Space Shuttle ACES suit was pressurized at one-quarter of the atmospheric pressure at sea level. This lower pressure helps with mobility, so it's easier to be able to move one's body and push through the range of motion in the suit. However, it also increases the chance of decompression sickness. So, in general, this trade-off always exists around what air pressure to prioritize pressurization for—whether it's a space suit or a space station environment.

When in space, especially for an extended period of time, astronauts tend to experience several physiological effects—including muscle atrophy, bone loss, damage to the cardiovascular system, spinal elongation, blood redistribution, and a spaceflight-associated term known as neuro-ocular syndrome. In this regard, a special new IVA suit called the SkinSuit can

offer some protection against many of the different effects that microgravity has on the human body. It's essentially a gravity-loading countermeasure suit to lessen musculoskeletal loss when in space.

There's also strong interest in bioelectronic suits that monitor vital signs like heart activity, respiration, blood flow, and oxygen levels and respond with pneumatic chambers integrated within the suit to mitigate the effects of weightlessness on the body.

BIOELECTRICAL SUIT

Next-Generation EVA Space Suits

EVA space suits are for any activity that takes the astronaut outside of the space station. When an astronaut works directly in the vacuum of space, the suit requirements need to change. Now, the suits must apply pressure to astronauts' bodies to simulate the kind of environment that humans evolved to live in. Without this pressure, the water in their bodies would boil away, so it's a critical aspect of human spaceflight in being able to go safely outside of one's vehicle.

With the mission to return astronauts to the Moon and then on to Mars, the need for EVA suits is a top priority. Designed to be more comfortable and flexible than the suits used during the Apollo missions, they will allow astronauts to do better science for longer periods of time on the lunar surface—and eventually even the Martian surface.

For example, the Axiom space suit is a next-generation EVA suit that will be used on the Artemis III mission going back to the Moon. It will be much more flexible than previous space suits. Axiom is putting a lot more engineering into the joints of the suit, into the fabrics used, and into how it is pressurized—so that it becomes easier for crew members to move in the suit while they're working.

To protect astronauts, traditional EVA suits have been gas pressurized. However, putting a pressurized atmosphere around an astronaut in a balloon makes the suit very immobile. It's also very heavy and hard to work against, but that's the current technology. Another option is to apply pressure to someone directly on the body—mechanical counterpressure—which would result in a very tight-fitting, skintight suit called a BioSuit.

In this regard, scientists are looking to make astronauts much more mobile if they can apply the technology and pressure directly to the skin to keep them alive. The huge advantage of this is that it is a very lightweight system. In addition, Axiom has designed a smaller compact backpack—the life support system on an astronaut's back—so that they can maintain mobility and flexibility.

NASA astronauts attired in training versions of their **SHUTTLE LAUNCH AND ENTRY SUITS**

Putting the pressure directly to the skin through a skintight suit also has a huge safety advantage. If an astronaut gets any kind of puncture in a big gas-pressurized suit, it's game over. They have to get back into a safe habitat. However, if the pressure is part of the suit and directly on skin and the suit gets a little scratch or abrasion, they could just put a smart ACE bandage over it and keep doing their EVA or space walk.

The BioSuit Helmet

The idea of the BioSuit is that an astronaut has mechanical counterpressure so that their body doesn't have an atmosphere like traditional suits. However, at the neck, they can't have a second skin around their face. So, Trotti & Associates have proposed the design of a helmet that brings the air from a life support system and all the related equipment to keep an astronaut alive. The helmet is very different from the present helmets, as it moves with the astronaut's head—very much like a motorcycle helmet that is attached to the mechanical counterpressure suit. It pivots and has a bearing that moves with the astronaut. This ability to have more visibility sideways and so on as one moves their head is therefore a critical piece of the helmet's design.

The BioSuit helmet is also extremely light. It's not as tight as a motorcycle helmet, but the idea is to have a small helmet that has the same visors as traditional helmets because it is important to protect the astronaut from solar radiation. In addition, one of the most important changes will be the heads-up displays—the amount of information one can project to the astronaut as they are walking on the surface. The BioSuit helmet would be a much more intelligent helmet and system than the one used today.

The challenge of keeping humans alive in space is as much about technological innovation as it is about human character and ingenuity. Areas such as radiation mitigation, ECLSS, and the engineering of space suits represent much more than just scientific progress. They embody the spirit of problem-solving and creative solutions that define space exploration. As humans continue to push the boundaries of what is possible in space, the insights gained hold the promise of benefiting humanity on a broader scale—from devising health treatments for cancer and enhancing environmental sustainability to improving homes on Earth in the face of climate change.

7

The Future of Food in Space

As on Earth, what people eat in space isn't just about acquiring the necessary number of calories to function optimally. Food is about fuel, and astronauts burn more calories and require more nutrients to stay healthy in microgravity than on Earth. What they consume must meet these demands. But eating is also about selection, taste, texture, aroma, and a time to share experiences and bond with each other—all things that people need to preserve as they venture further away from home. In this episode, you'll explore the practical challenges of eating in microgravity when food just floats away, how food can be an especially important tool for maintaining morale in space, and the future of food for missions to Mars and beyond—where having variety and fresh supplies will present unique challenges.

The Challenges of Food in Space

One of the unique challenges space poses with respect to food is the astronauts' physiology. They often have decreased appetites during missions because the ability to smell is reduced, and they can't taste as much because their sinuses are so impacted. In addition, the dry environment also reduces the ability of taste buds to function.

Another challenge is that food choices are rather limited in space. Foods must be shelf stable, meaning they can remain fresh while stored at room temperature and for an extended period of time. Most food is semi-liquid or freeze-dried in space because it weighs less and does not shed crumbs in microgravity. NASA is very anti-crumb because crumbs can interfere with electronics and the ECLSS machinery that is so critical to the safe functioning of a habitat.

Crew of the first manned Skylab mission dine on SKYLAB SPACE FOOD in the wardroom

Further, a space environment has limited food preparation capabilities and relatively limited storage. Food mass and volume are already considerations, but these will be even more constrained on missions to the Moon and Mars.

In addition, just like on Earth, scientists have to think about food safety, so they need to make sure that all of the food being provided to crews is safe and free from bacteria and other irritants.

The Importance of Food in Space

Food plays a significant role in the mental health and well-being of astronauts, and this fact has drawn more attention in recent decades. While roughly 80% of astronauts' diet is from a standard menu, on the ISS, they now get to choose about 20% of their food because it is good for their mental health. The resupply missions to the ISS in LEO, which include some fresh fruits and vegetables, also address this behavioral need and have proven to be quite popular. In addition, astronauts report that food selection provides important psychological benefits.

Crew sharing a SPECIAL THANKSGIVING MEAL aboard the International Space Station

The other significant aspect about food in space is its communal nature. When astronauts visit the ISS, everyone gets sent up with slightly different food, and the amounts of the good stuff—chocolates, candy, tea, and coffee—can vary. However, reports have shown crews coming together on the ISS, essentially aggregating their treats and then sharing them equally among the crew. While an astronaut's representative country or organization may be sending them up with things, they're one crew up there, and they're going to share their resources and the joy they provide equally. Doing so can

help overcome some of the sensory and food monotony they experience eating the same thing every day for weeks and months, and it's also a way of getting to know the other crewmates.

The NASA Food Lab

The current standard for the development of food for space is the NASA Food Lab. According to the Food Lab, food for the crew must meet certain criteria, the first of which is safety. Food must be free from risk to astronauts and vehicles. Current food safety requirements and methods will not easily transfer to long-duration missions.

The second is nutrition. NASA food must not only prevent nutrition deficiencies but also promote health and performance. The next is palatability—if the food doesn't taste good, even the most disciplined astronauts will tire of it, and it will not be able to support astronauts' health, performance, and morale.

Beyond palatability is the importance of variety. Different food types, textures, and flavors will be needed to encourage consumption. Next is usability: The food system must allow for fast preparation and be easy to use while also remaining within the safety margins for the crew—for example, eliminating the risk of burns and also maintaining safety for the vehicles.

The next criterion is resource minimization. So, any food system needs to consider mass, volume, water use, power needs, equipment, and crew time as well as wastewater, packaging, and biological waste produced—a lot of considerations around how to make sure the food system is efficient in space.

Reliability is next. If food spoils or doesn't grow properly or if equipment fails, the impact on astronauts would be significant. Finally, there is stability. The current design for Mars missions requires that food maintains acceptable taste and nutrition for at least 5 years and also meets restricted mass, volume, and storage requirements.

The Future of Food in Space

The requirement of stability is more important for long-duration missions like going to Mars, as they will be much more challenging. With no resupply from Earth of fresh fruits and vegetables or even semi-shelf-stable foods, if astronauts do want produce, they'll need to grow it on their own in situ, on the spaceship, or within the space station on the surface. And because of the perchlorates in the Martian regolith, plants could only be grown in rather elaborate, self-contained greenhouses.

Growing plants in space has its advantages. They can scrub carbon dioxide from the air, helping astronauts revitalize the air—and plants take carbon dioxide and produce oxygen as part of their respiration. Eating plants can also help diversify the menu, and tending to plants provides a well-known benefit of psychological well-being for the crew.

FIRST GROWTH TEST OF CROPS
in the International Space Station

As scientists begin to think about innovation in the types of foods for crews, they'd like to move beyond freeze-dried food, which removes the probiotics. Fermented foods are better for the gut microbiome, and the process of fermentation can be taken safely into the space environment. Another benefit of foods like miso, sourdough, and pickles is that they bring a richer umami taste to improve the flavor intensification and the joy of eating the food.

In addition to fermented food, space missions need new technologies for how to grow fresh produce in orbit. Activities like NASA's Veggie Mission have been going on now for several years on the ISS. In addition, the Aurelia Institute is focused on developing its Green Vault—a small green wall for growing vegetables and herbs for nutrition and flavor.

In 2015, astronauts grew romaine lettuce aboard the ISS for the first time, but growing plants in microgravity is difficult. When watering a plant on Earth, water moves through the soil because of gravity and helps nourish the roots—with excess water generally draining away. In microgravity, water does not behave like this. Instead, it adheres to the roots, which can cause the plant to drown or ultimately cause other blights and issues with its health.

So, to avoid drowning, hydroponics and aeroponics are the preferred methods for growing food in space. Hydroponics is where the plants are in a contained and orchestrated amount of water, and aeroponics is where they are grown in air but are sprayed with water and fertilizer. The Green Vault uses an aeroponics approach that will support a range of plants for oxygen production, food, and the sheer joy of taking care of beautiful greenery.

Kitchen Implement Innovation

Beyond fermentation and green vaults, experts are also thinking about the design of new kitchen implements. Even the design of kitchens and food utensils may change over time as the culture of food in space evolves. One of the best examples of this is astronaut Don Pettit's work on the zero-g cup, which is an incredible design leveraging capillary action and the tendency of surface tension to dominate in liquids in microgravity to essentially trap fluid in a cup so that astronauts can have an open cup of liquid on a space station

while floating. The consequence of this is that astronauts are able to enjoy the aroma of a coffee—in addition to sufficiently trapping the liquid so that it doesn't escape and float out through the habitat.

If an astronaut lets go of something in space, it's apt to float away. Within a kitchen environment, instead of being able to rely on setting something down on a counter while cooking, astronauts need to stick it to a surface. Therefore, Velcro is a popular option for all of the different things they need to adhere to the walls around a kitchen.

Even a dining room table could look different—for example, a table that's spherical or a torus so that people can join from all different orientations. It's clear that humans, especially when breaking bread, want to be able to see someone's face in the expected orientation, so the future might see less of upside-down dining tables in space and more of new cultural artifacts around the kitchen, dining, and breaking-bread space.

Scientists know that food and the experience of eating can elicit intense emotions, and they're now thinking about ways that technology can leverage this for better mental health. Several years ago at MIT, researchers hosted an interesting food workshop with astronauts Katie Coleman and Paolo Nespoli. When Paolo had a virtual reality headset on for an exploration of food and new environments, he immediately went to Google Maps and navigated to the Italian village where he was from—and where he had these memories of home-cooked meals in his favorite restaurant.

The reason this is important is that he chose to take himself to a place where he remembered the terroir, scent, smell, and context. Such insights have inspired scientists to look into ways to use virtual reality experiences like this in the future to provide the importance of context and sense of memory when it comes to growing, cooking, eating, and enjoying a dinner together in space.

Looking ahead, the plans for growing nutritious but delicious food on long missions are as critical as they are fascinating. And as humanity pushes further out into the solar system, it's worth mentioning that the lessons learned will not only support astronauts but could also influence how people manage food right here on Earth.

8

From Surviving to Thriving in Space

ASTRONAUTS AND CIVILIANS CANNOT JUST LIVE IN space—they also need to be able to thrive there. For longer-duration missions, helping individuals to perform at their best will be necessary to reach space exploration goals. In this episode, you'll focus on how human beings might unleash their full potential in space. You'll begin by examining how scientists can improve the bodily and cognitive health of crews so that they live and work together optimally. Then, you'll consider how microgravity opens up new opportunities for design and movement in 3D spaces that can only occur while floating sublimely in orbit. Finally, you'll explore the importance of leisure activities and some of the ways that creative expression could evolve into entirely new activities unique to life in space.

Weightlessness

Weightlessness—the cause of space sickness—can induce symptoms of motion sickness like nausea or dizziness and fatigue. While most people adapt quite quickly over time, space sickness in the early stages of a mission can reduce cognitive abilities.

One way to reduce or even eliminate space sickness is to try and enable a smooth transition from life on Earth to living in space and to give crews explicit time when they first arrive to calibrate without loading on extensive tasks right away. Certain drugs, like scopolamine, can also be used to mitigate symptoms of cognitive dissonance and improve one's ability to withstand the effects of microgravity. Fortunately, such feelings don't usually last long after getting acclimated.

Beyond some of the challenges of motion sickness, weightlessness can also impact spatial awareness—the knowledge of where one's body parts are at any given time—and thus the ability to navigate environments. MIT has run a series of experiments over the years—and more recently in the MIT Space Exploration Initiative—around solving 3D mazes while floating and while wearing virtual reality headsets in different gravitational conditions so that they can learn a little more about how people understand the placement and movement of their bodies in zero-g.

Living in Microgravity

When it comes to bodily and cognitive health, the effects of living in close proximity with other people for long periods of time in isolated, confined, and extreme (ICE) environments introduce unique health and cognitive challenges. Space environments are considered closed systems—autonomous societies where behavioral health, social dynamics, and team performance all impact each other. For this reason, NASA takes a lot of care in the selection of a crew and who's brought together for a mission.

A Skylab 3 science pilot in his SLEEP RESTRAINTS in the crew quarters of the Orbital Workshop

Aside from the importance of food, areas that have been studied to improve performance in ICE environments are exercise and physical activity; the importance of circadian rhythms and when astronauts are sleeping, waking, or working; habitat design; and layout.

Without gravity, traditional notions of floors, walls, and ceilings can be entirely reimagined. People are used to living on a 2D plane on Earth. Their rooms may have high ceilings, but they're never up in that physical space—they're always on the floor. Such a reality changes completely in a microgravity space station, where one can float through all parts of the open volume—all parts of the structure—equally.

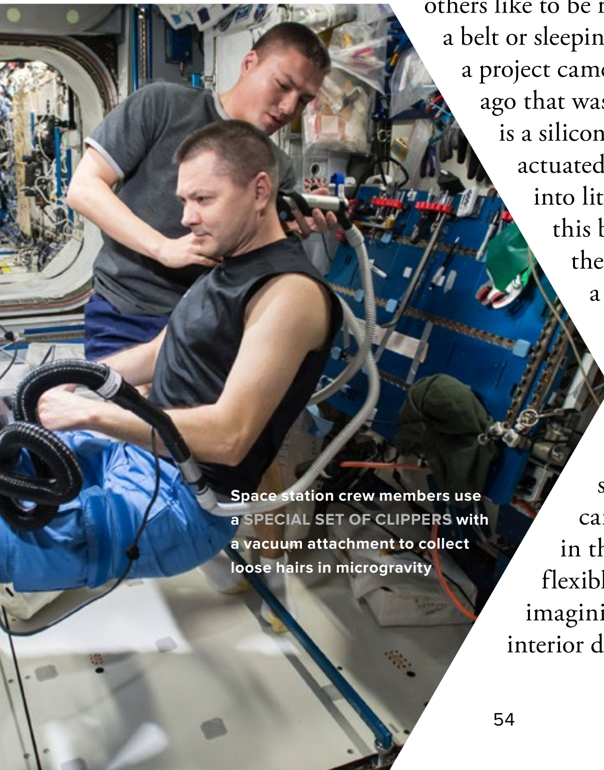
Therefore, a need exists to design spherical interior spaces or furniture that can expand like an amoeba up a wall and around other obstacles. In this regard, an architecture that can change according to the needs of its

inhabitants—being there when needed and disappearing when not needed—further expands the limited spaces of crew and compartments and provides the flexibility needed in human spaceflight.

Design Innovations in Space

In space, gravity is a force that disappears out of the equation of design. In addition, due to zero atmospheric pressure, astronauts are inside extremely high-pressure vessels and have the freedom of flying. So, taking those two things out of the design equation, a whole new world to explore happens where one can use all surfaces and move in an axis, with an astronaut flying from horizontal to going down or up to a different module.

For example, while some astronauts like to sleep without being restrained on anything—just floating around all night—others like to be restrained against a wall with a belt or sleeping bag. In relation to this, a project came out of MIT a few years ago that was dubbed Spatial Flux. It is a silicone tentacle, pneumatically actuated with air that is pumped into little channels. Essentially, this body-length tentacle grips the astronaut and provides a sense of embrace and comfort like when they're lying on a bed on Earth. One of the things that astronauts report is that they struggle to get that sense of comfort because they cannot truly rest their weight in the same way. Thus, providing flexible alternatives is critical for imagining the next generation of interior designs.



Space station crew members use a SPECIAL SET OF CLIPPERS with a vacuum attachment to collect loose hairs in microgravity

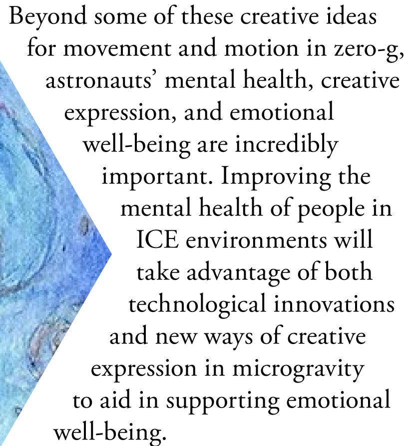
In microgravity environments, astronauts will need new accessories to move more accurately. The challenge lies in determining how astronauts can control their movement without gravity guiding and shaping where they can move. A funny challenge in space that astronauts often report is that if their wingspan is shorter than the diameter of the space they're in, they can get stuck floating in the middle—and because one cannot swim through air, it's extremely hard to get back to one of the surfaces of the habitat and regain control.

With this in mind, scientists at MIT have developed the Orbit Weaver, which is a spider-inspired 3D movement mechanism. Essentially, it's a small artifact that sits in the palm of an astronaut's hand—a wearable device that shoots out a magnet-tipped string. The magnet attaches to anything that's ferromagnetic. Then, the astronaut can essentially reel themselves in and pull themselves over to the site where the string is attached.

Another project inspired by the sea—specifically by seahorses—is a multipurpose tail called Space Human. It's essentially a prosthetic that comes with a vest, and the tail expands out the back. It's pneumatically actuated, so the astronaut pumps air into it to make it curl and grip around things. While their hands are free to do whatever they need to do, the tail can grip onto a bar or other object to stabilize them while they're working and floating in zero-g.

One of the most interesting aspects of life in zero-g is that humans' legs are vastly overpowered. All of these muscles in the lower body have adapted over millennia because of the need to fight gravity. But when someone is in space, it's much more important to have extra hands and gripping mechanisms—maybe a future prosthetic tail—than it is to be able to work with one's normal human limbs.

Mental Health and Creative Expression



Beyond some of these creative ideas for movement and motion in zero-g, astronauts' mental health, creative expression, and emotional well-being are incredibly important. Improving the mental health of people in ICE environments will take advantage of both technological innovations and new ways of creative expression in microgravity to aid in supporting emotional well-being.

Nicole Stotts WATERCOLOR WORK **in space**

Mental health, enjoyment, and being transported back to Earth are all important experiences, and scientists know that they need to design these factors into the future of virtual reality or augmented reality experiences, particularly for long-duration space missions. They're working on the notion of a personal holodeck—small space pods—that can transform the experienced environment, providing a contained space for a person to escape, unwind, and entertain themselves. It can be fully or partially immersive, depending on the available space and energy.

Beyond such interior design elements that make it a compelling day-to-day life in space, it is also important to think about what makes it a life worth living in space. What are some of the special things that make life worth living on Earth? When it comes to the arts, rather than simply importing techniques from Earth, microgravity presents scientists with the opportunity to build new cultural artifacts—new art forms unique to life in space.

For instance, instead of drawing on a standard 2D surface, in space, drawing can take place in a 3D area. Alex Hope at MIT developed a project known as Space/Craft, drawing on the long tradition of handcraft, using heated glue to draw 3D sculptures that float into forms that could not be created on Earth.

Many other thought-provoking ways exist to create art in microgravity. The visual arts are not the only creative mediums that can be transformed in space. Music may also undergo a renaissance. Todd Machover's lab Opera of the Future at the MIT Space Exploration Initiative developed a collection of musical instruments based on weightless movement and new types of sound production.

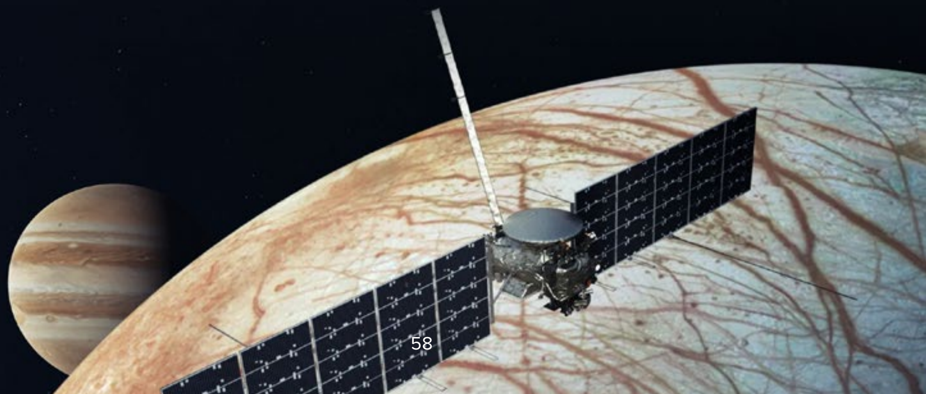
These musical instruments—the first one has been dubbed the Telemetron—only work in a zero-g environment. They don't make music in a typical Earth-based environment—they have to be in space or floating to be able to perform. They're a wonderful example of the rich array of artifacts that people will have a chance to experience in this next generation—an opening up of a different vision for life in space.

While it's true that the extreme environments of space present all manner of dangerous and serious challenges, if people only focus on these, they risk losing sight of all the ways they can flourish away from Earth. In this regard, technology and art are being used to elevate and enrich the human experience in space, as humans can only be said to thrive there if they bring their entire selves off world.

9

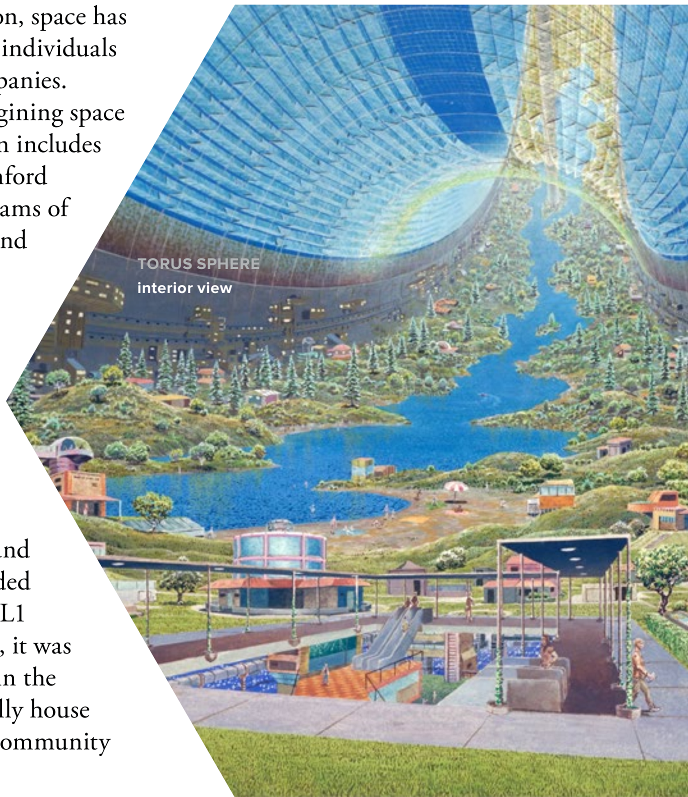
Space Tourism and the Overview Effect

ONCE A MERE FANTASY, THE OPPORTUNITY FOR travelers to journey into space is becoming a reality, marking a new era for people from all walks of life to be inspired and humbled like never before. The market for space tourism is growing, and with it comes the ability for people to experience the overview effect—a remarkable shift in perspective that many people who travel into space share. In this episode, you'll take a look at the space tourism opportunities available now and in the future and explore the kinds of activities that a trip into microgravity makes possible.



Space as a Tourist Destination

As a tourist destination, space has long been a dream of individuals and commercial companies. The pinnacle for imagining space as a robust destination includes concepts like the Stanford Torus—devised by teams of NASA visionaries—and the massive cylinders envisaged by Jerry O'Neill.



TORUS SPHERE
interior view

The Stanford Torus is the concept of a huge donut in space—a huge ring meant to sustain around 10,000 people. Intended to be put at either an L1 or L2 Lagrange point, it was expected to be ready in the 1990s and to essentially house an entire settlement community in space.

An O'Neill cylinder is a massive space station. It's a long cylinder and might be 4 or 5 kilometers long and perhaps 1 or 2 kilometers in diameter. It's rotating because the centrifugal force of that rotation creates artificial gravity. So, imagine the humans on the surface of that rotating cylinder experiencing gravity, looking up into the sky—the volume of the sky of the cylinder is where they would have their crops, habitations, and other infrastructure. The whole idea is that humans would live and work permanently in space at these stable orbits within a self-sustaining cylinder, which would have the ability to create energy and food and recycle a lot of materials.

Space Tourism Now

The demographic for space tourism is people who are going to space on purpose because they want to experience it and who are probably paying a lot to do so. So, which companies currently offer this opportunity for either suborbital or orbital flights?

Virgin Galactic has its suborbital space plane, while Blue Origin has its suborbital experience on New Shepard. Boeing and SpaceX also have interesting plans to be able to bring people—people from the public, not just astronauts—on experiences like these.

As one of the main outlets for suborbital flights, Blue Origin has pushed the boundaries of space tourism and the ways it can open up space for the rest of humanity. Costs are coming down, while access is going up, which means that new communities are coming to space. In this regard, space is becoming more accessible, and anyone can now see themselves in that world. As humanity starts to move toward a future of millions of people living and working in space, this first step is helping to open those doors so that more people can walk through.

Eventually, people will move from short trips up to the edge of space to going up to space just because they want to. This idea is extremely exciting when thinking about what that means with regard to going on a vacation. What does it mean to go and live in space? And this can be extended to commercial activities, the arts, and education. People can go up to space because they want to understand what it looks like to see their planet and the thin blue line of their atmosphere that protects us all.

Experiencing Space on Blue Origin

Dylan Taylor, who flew on the New Shepard 19 mission, has experienced space on a Blue Origin flight. Here are some of his recollections:

> So, to get ready for this, you go through countless simulations of what your spaceflight is going to be like. A lot of it is auditory training. You're looking

at mission time; you're understanding what you're going to hear, what you're going to experience; and you're practicing that over and over and over again as a crew. We rehearsed literally everything—even walking across the bridge to get in the capsule and ringing the bell. That was part of our training.

But one of the consequences is, on launch day, you're completely comfortable. I would have thought that I would be terrified on launch day. How can you not be? You're strapped to a controlled explosion, and there's maybe a one-in-a-hundred chance you don't make it home. Logically, you should be fearful. And the fact is, I wasn't. My heart rate on launch was 62. And it wasn't just me—it was the entire crew. And I think [it goes] back to the training. You've rehearsed this. Your brain's saying, "I know what this is. I've done this. I've experienced this." The training really makes you quite comfortable.

The launch itself [was] remarkable. Thirty-five minutes from when you're sealed in the capsule to when you're taken out of the capsule. The ride up is fun. It's about 4-and-a-half minutes. You're going supersonic in 27 seconds. And once you're in space and you're able to unstrap and [are] in microgravity looking at the Earth, that's another 4-and-a-half minutes or so. And the way down is a bit longer, of course, because the parachutes are deployed.

But what's interesting is that I experience[d] very severe time dilation. On the way up, it was compressed. It seemed much shorter than what it was. And then, thankfully, the most important part—being in space [and] looking at the Earth—

that was much longer. Everything was very elongated. And they say the perception of time has to do with the mental cycles you're clocking, and so I believe that because you're in this sense of awe and wonder and your brain's going haywire, so to speak, that really elongates the experience of time.

Being in space—looking at the Earth—is a completely life-changing experience. Leading up to it, you have to file a so-called zero-gravity plan. So, you know what you're going to be doing. You've thought about it ahead of time. But also, the other crew members know what you're doing. You're all together in three-dimensional space, and you all have an awareness of what the others are doing. And for me, one thing was very clear. I didn't want to do the proverbial flips and acrobatics—because you can do that on a parabolic zero-g flight. The one thing I wanted to experience was seeing the Earth from space.

In Blue Origin, New Shepard [has] very large, sloping windows. So, what I decided to do was go to the window and turn myself upside down. Why upside down? There is no up and down in space, but when you've trained in a capsule for weeks, you perceive up and down because your brain has experienced that within gravity. And I wanted to totally disrupt that notion.

So, I went to the window, turned myself upside down, and the consequence of that [was that] the chair was not in my field of view—nothing was in my field of view. So essentially, I'm floating; I'm hovering over the Earth—completely mind-blowing situation. And it literally took my breath away, where I gasped, and I said, "Oh my gosh, oh

> my gosh!" It was the first time I'd seen the Earth from space. So just a remarkable, remarkable moment.

The Overview Effect

In 1968, one of the most significant photographs ever captured was taken by astronaut Bill Anders aboard Apollo 8. As the command module orbited the Moon, Earth slowly appeared behind the desolate landscape in all of its blue-marble glory. Called Earthrise, it allowed people across the globe to see their planet from a completely different perspective—small, fragile, and remarkably beautiful.

As astronauts frequently report, seeing Earth from space triggers a transformational experience known as the overview effect. Coined by Frank White, the term refers to the powerful, emotional, and often very long-lasting feeling that rises up in astronauts when they see Earth from space for the first time. This profound psychological moment has produced tears in seasoned fighter pilots and led even the best-trained human beings to go off script as they go quiet with awe for the majesty of the planet. Documented time and time again, it's a recognized effect that captures the heart of many space flyers and has been a key focus of democratizing access to space. How can more citizens of Earth share in this experience?

The overview effect is a shift in perception that results from a combination of factors that can only occur in spaceflight. Number one is an exhilarating ride up and back. Second is the visceral experience of being in sustained freefall or microgravity, which cannot be replicated on Earth—a physical sensation throughout your body that affects everything you do due to being in a fundamentally different physical environment. Third is the view out the window—the most poignant, beautiful, ever-changing view in the solar system: the curvature of Earth, the thinness of the atmosphere, the change in weather patterns, cloud formations, waves in the ocean, the colors, the lighting, everything changing all the time. Added to this is the knowledge that this thing you're looking at is the only place in the known universe where life can occur.

NASA astronaut LOOKS THROUGH A WINDOW in the cupola of the International Space Station

The combination of these three things—the ride of your life, the unreproducible visceral experience of being in sustained freefall, and the view out the window—combine to create the overview effect. So, how could flying hundreds of thousands of people a year to experience the overview effect—particularly since, at the beginning, they will be the richest and most powerful people—help society today?

First and foremost, space is a tool for transformation. It helps humans to understand that we're fish in a fishbowl and to get out of that environment and see things as they truly are. Experiencing this cognitive shift—having space as a canvas where we can reimagine what humanity can be—is a very powerful notion.

If one buys into such an idea, it's all about getting more people out there and building infrastructure in space. For example, some dream of creating commercial space stations; imagine having a G20 Summit or a UN Security Council meeting up there. People seeing Earth in context would perhaps lead to different outcomes.

Ultimately, space exploration—whether it's for tourism, science and engineering, or even off-worlding—is a reminder that visiting space is profoundly also about protecting Earth. As the opportunity to travel into space is made available to a greater number of people, there will be much more to it than just the thrill of weightlessness and the destination itself. The overview effect is a reminder that behind space tourism lies the potential for a unifying perspective of humanity and the realization that Earth is a fragile planet deserving of our utmost care and respect.

10

Using Space to Benefit Life on Earth

EARTH IS UNIQUE IN THE SOLAR SYSTEM. WITH VAST oceans and a temperate climate, life can be found almost everywhere on the globe. But in recent decades, humanity has damaged its fragile home. Heavy industry has polluted the planet and the atmosphere, and people are now seeing the impact this is having on the biosphere. In this episode, you'll consider some of the ways humans can move industry out into space, develop clean energy for the surface of Earth, and revolutionize medicine to benefit all of humanity.

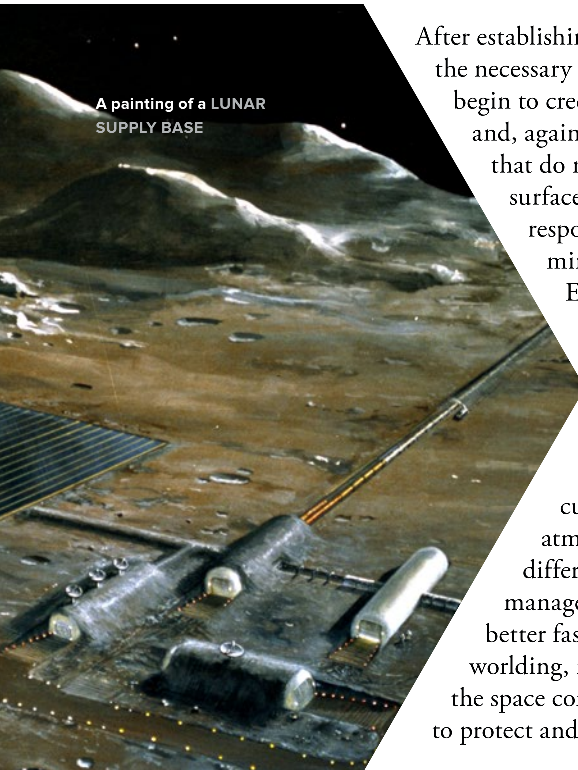
Resource Extraction in Space

The Moon has a lot of resources. Water ice can be purified—with the hydrogen and oxygen split—and then used for propellant to promote deep space exploration. Doing this would allow the Moon to become a gateway to the rest of the solar system. In addition, helium-3—which is much more abundant on the Moon than on Earth—is incredibly important as a potential future method for powering fusion reactors on Earth and supercooling quantum computing. It's already used in MRI technology for medical imaging and in national security for vetting materials coming into ports.

Other resources include minerals like iron, found at around 15% in the Maria basalts; titanium, of which the Sea of Tranquility on the Moon has some of the highest levels; aluminum, about 10% to 18% by weight; and anorthite, which is a mineral that is rare on Earth but abundant on the Moon. Silicon—about 20% by weight in regolith—could also be used to produce solar panels for space-based solar power.

Several companies are working on the most efficient way to extract the Moon's resources and bring them back to Earth. As those technologies mature, the benefits for life on Earth could improve the climate, help restore aspects of the environment, and create jobs and economic wealth. One of the more inventive ways of taking those materials off the Moon for processing could be by using a mass driver—an electromagnetic sled that slingshots mass into space.

Since the Moon is one-sixth the gravity of Earth and has essentially no atmosphere whatsoever, there's no drag on getting materials to orbit around the Moon. The idea would be to mine resources on the Moon, put them on a mass driver, sling them into the orbit of the Moon and into space, and then tug that to the Lagrangian points—these stable orbits that will not degrade for millions of years. These points are where you could build the infrastructure, such as an O'Neill cylinder, a foundry, or energy-generating infrastructure. Earth could become a wonderful, pristine national park, with all pollutive industries taken off it.



A painting of a LUNAR SUPPLY BASE

After establishing best practices and developing the necessary technology for this, we could begin to credibly explore asteroid mining—and, again, expand our access to resources that do not require damaging Earth's surface. The more we invest in responsible lunar and asteroid mining, the more we can protect Earth for generations to come.

It's also important to note that we're not just trying to shift from polluting Earth to polluting space. Certain industrial processes that are currently trapped under our atmosphere are fundamentally different in the vacuum and can be managed and contained in a much better fashion. As we explore off-worlding, it's critically important to treat the space commons with respect as we aim to protect and improve life on Earth.

Space-Based Solar Power

Another industry that could be transformed by space exploration is the energy sector. The hope is that at some point in the future, we'll be able to harness nuclear fusion on Earth—and the helium-3 from the Moon could be important for that. However, we don't need to wait for something as exotic as fusion in the near term.

Unless briefly occluded by a planet, a moon, or an asteroid, sunlight is continuous in space, so space-based solar power is not impacted by the intermittency problem that exists on Earth or by day-night cycles. Space-based solar power stands to deliver abundant, clean energy to the surface of Earth and anywhere on Earth at any time.

Two key approaches exist for space-based solar power. Both of them use large arrays in space above Earth's atmosphere, where they capture the photon energy and beam it down in the form of either microwaves or lasers to collecting stations on Earth for a new, clean energy solution.

The benefit of converting light energy into microwaves is that they pierce perfectly through the atmosphere, so there's much less efficiency loss when they're passing through clouds or other obstacles. The benefit of using lasers is that they are probably safer and can use photovoltaic arrays—solar panels on the ground—to capture the light coming down.

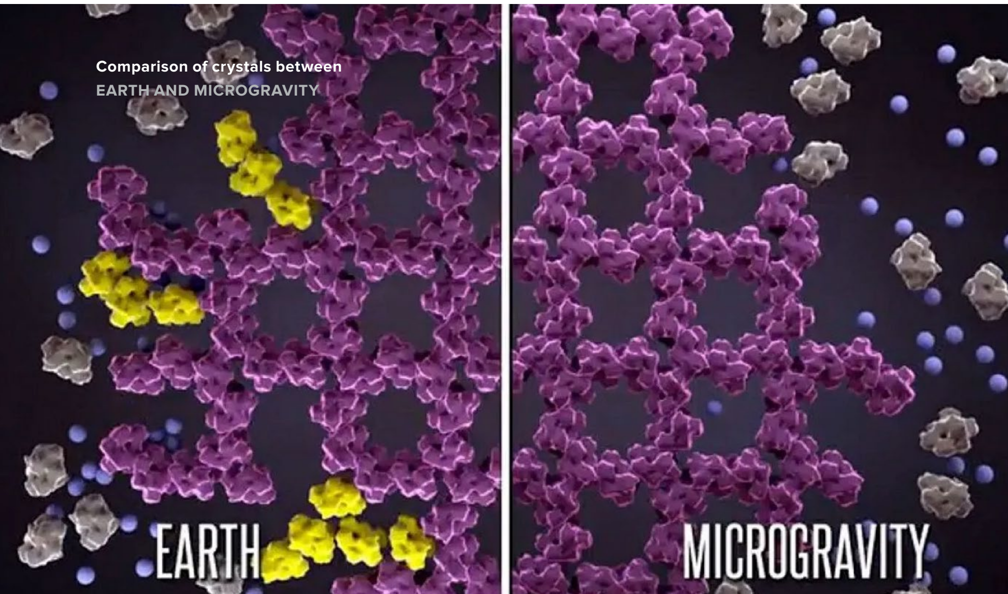
With solar arrays in space, we can transfer the energy using lasers to other space-based platforms in LEO, cislunar space, and Mars or other outposts. Thus, space-based solar power is an opportunity to go not only from space to Earth but also from space-to-space assets.

New Technologies in Orbit

The purpose of off-worlding is not just to take some of the harmful industries off Earth into space or to produce clean energy. Some helpful technologies can also benefit from space. Microgravity allows for processing materials and manufacturing in a way that cannot be achieved in a gravity environment. These benefits of microgravity derive from a few key principles of physics.

For instance, fluids behave very differently in microgravity. Instead of gravity pulling fluids down into a teardrop-like shape, surface tension dominates, and fluids stay spherical. Similarly, convection doesn't occur in microgravity because hotter, less dense fluids don't rise and fall the way they do in a gravity environment.

Another interesting phenomenon is that because of the lack of gravity, the sedimentation that usually happens in fluids or solutions for chemistry or biology products also doesn't occur. Things don't settle down. No gravity is pulling them in a particular direction. And so, one can play with much more uniform mixtures that stay in solution.



Comparison of crystals between
EARTH AND MICROGRAVITY

In this environment of space, scientists and engineers can develop technologies that would be impossible on Earth, which is what makes space so special. It's an example of a domain where people are able to create completely new types of products and think about framing these products and the use of space for the benefit of life on our planet.

A promising line of research is the development of artificial retinas that could one day restore the vision of people afflicted by retinitis pigmentosa and age-related macular degeneration. Protein-based artificial retinas use a layered production process that is difficult to achieve on Earth due to sedimentation. However, in microgravity, the precise layering of bacteriorhodopsin proteins can be achieved.

Another promising research area concerns how microgravity can sometimes accelerate disease, which means that certain types of cancer grow at an accelerated rate in microgravity. When that happens, you suddenly have a disease model where you can answer questions in months instead of years and have real advances in medicine and treatment. Microgravity also allows

for organoid growth for tissue development—such as for organ transplants. This concept might help reduce the need for animal testing by relying instead on artificially generated organ tissue that grows quite well in microgravity.

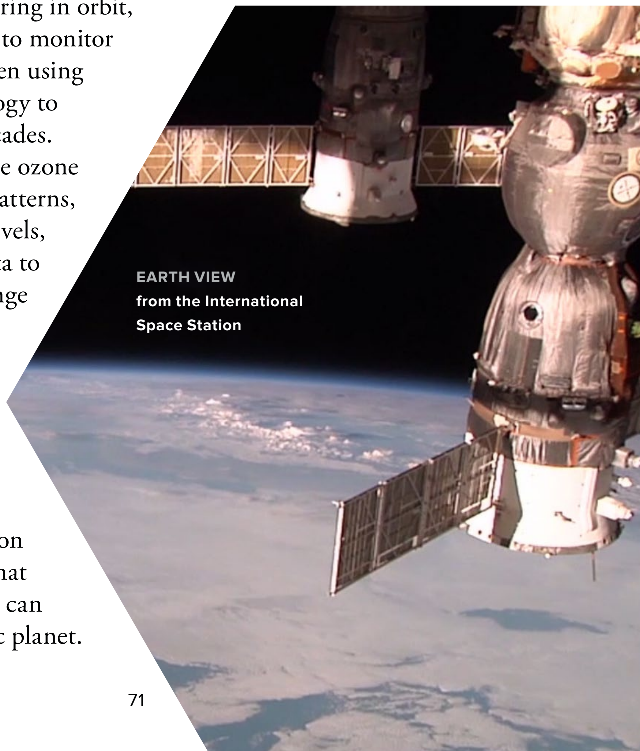
These microgravity principles that deeply affect biology and orbit also affect the organization of matter at small scales for material science. NASA has long explored novel crystal growth with the hope that purer and more perfect crystal formations will assist with things like semiconductor manufacturing.

Novel extrusion—essentially extruding liquid and UV curing it to harden it—will allow for all sorts of next-generation structures, lattices, frames, and large deployable structures that would sag on Earth due to gravity but can be extruded at almost infinite length in microgravity.

Earth Mission Control

Beyond in situ manufacturing in orbit, experts can also use space to monitor Earth. They've already been using off-world satellite technology to monitor the planet for decades. Their ability to observe the ozone layer, scrutinize weather patterns, measure greenhouse gas levels, and leverage all of this data to help mitigate climate change is a true achievement.

Space offers an incredible vantage point to look down on Earth and see our humanity and oneness. A new project called Earth Mission Control aims to provide that to everyone so that people can perceive Earth as a holistic planet.



EARTH VIEW from the International Space Station

Over 50% of our climate variables come from Earth-observing satellites. Eyes are on the planet, monitoring carbon dioxide, methane, and so on—the vital signs of Earth. Now, imagine immersing an individual in an Earth Mission Control and giving them a holistic overview that's great for understanding and knowledge. What they care about might be, for example, "I want to zoom right into Cambridge, Massachusetts—the Boston area. What are the things I need to be concerned about for climate in my city?" Maybe it's flooding or rainfall. They can type in their zip code, and the Earth Mission Control can zoom in and give them that data. The idea is about spreading information and giving people agency.

Earth Mission Control puts people in simulations where they can pick the variables—for example, whether they care about carbon dioxide emissions or agriculture—and provides ideas about what they can do about it and what actions they can take. These actions are usually simple, such as walk to school, share a bike, or eat certain foods today. The notion concerns a narrative and storytelling and putting people in the environment to empower them in their decision-making and adapt to some of the climate effects and mitigate them.

Off-worlding is a multidimensional opportunity. It's about protecting and preserving Earth as our garden planet while leveraging the space environment to create things that could never be achieved before. In short, off-worlding is about using space to benefit life on Earth.

11

Finding Life in the Universe

THE UNIVERSE IS VAST, WITH HUNDREDS OF BILLIONS of galaxies and the potential for trillions of planets. Is there life beyond Earth, or are humans alone? And how could humanity know? Researchers have found life in some of the most inhospitable places on Earth, so this raises the possibility that they might find extraterrestrial life one day. In this episode, you'll explore whether life may exist in the universe and what researchers are doing now and will do in the future to find it. You'll also examine the planetary protection measures that are in place to safeguard both humans and whatever they may discover.

Life on Earth

Life as we understand it includes a few key components: being responsive to the environment one is living in; having the ability to grow; having a metabolism, or the ability to transform energy; and, fundamentally, reproducing and creating new life. With this understanding of what constitutes life, astrobiology focuses on three main areas of research: first, the study of origins, early evolution, and the distribution of life on Earth; second, the search for biosignatures—records of past or present life; and, third, the study of habitable environments in our solar system and beyond.

On Earth, life is found in almost every environment. When those environments are punishing, the life forms found there are known as extremophiles. Regarding microbes that can exist in the stratosphere, they have evolved the ability to withstand radiation, frigid temperatures, desiccation, and low atmospheric pressure. At hydrothermal vents on the ocean floor, life has evolved in the presence of toxic gases, temperatures more than 400°C, and the total absence of sunlight. Such extremophiles give astrobiologists hope of finding life beyond Earth in other extreme environments.

The Search for Life

When searching for biosignatures of past or present life, scientists look for four things: carbon-based components, liquid water, environmental stability, and an energy source.

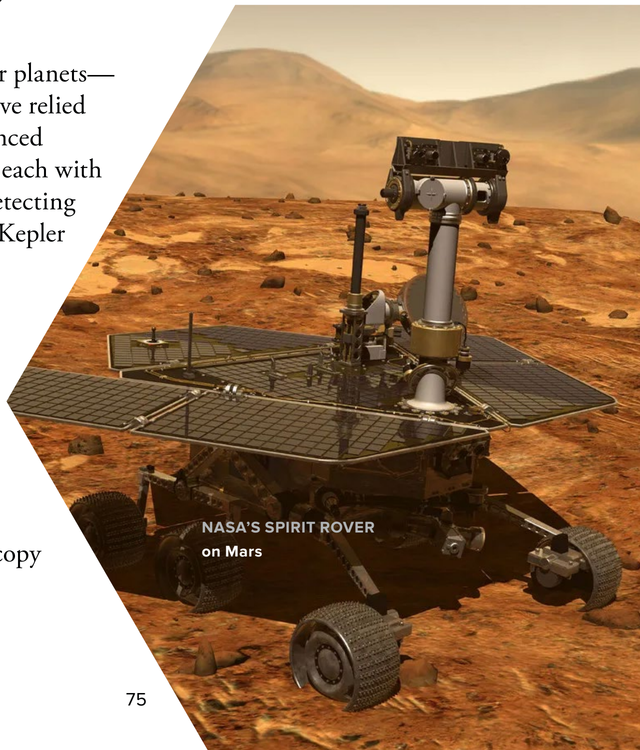
Carbon is the basis for all life on Earth. Carbon atoms readily bond to other carbon atoms and can build complex molecules that could carry biological information. In terms of where we search for life, liquid water is critical, as it allows for the formation of complex carbon-based molecules. With regard to environmental stability for life to evolve, scientists look for planets that might have a magnetosphere like Earth's, which helps keep and trap an atmosphere and also moderates temperature with limited fluctuations. For an energy source, scientists look for red dwarfs—sun-like stars with planets in the

Goldilocks zone, which means they're close enough to their sun to get enough solar energy but not so far from their sun to be too cold. They also look for things like hydrothermal and volcanic activity.

But if there is silicon-based life, do scientists have the ability to detect it? While most astrobiologists think about carbon-based life when they're thinking about life beyond Earth, there's another field within astrobiology—the search for agnostic biosignatures. So, rather than trying to think about life as one knows it, based on Earth constraints, what would be the basic things that life needs to do to distinguish it from an abiological background?

The operational definition of life is a self-sustaining chemical system that's capable of Darwinian evolution. In this regard, scientists would look for things that don't need to be specific-element based—like energy gradients or evidence of metabolism. So, while most astrobiologists still generally think about and favor carbon-based life, they don't exclude other types of life. They always need to think about what they don't know and try to remove themselves from what might be called earth-based thinking.

In the search for extrasolar planets—or exoplanets—experts have relied on some of the most advanced technology ever invented, each with a particular method for detecting planets. For example, the Kepler telescope uses the transit method, which is useful when a planet orbiting a star passes between that star and us. When this happens, the brightness of the star dims just a bit, indicating that an exoplanet is transiting in front of the star. Spectroscopy

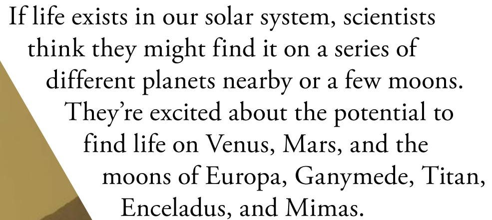


NASA'S SPIRIT ROVER on Mars

then analyzes what the makeup of the atmosphere may be and whether it's similar to Earth's. This approach is the most widely used method for detecting exoplanets.

The goal is to find Earth-sized planets in habitable zones and examine their atmospheres spectroscopically to detect certain biosignatures of methane, oxygen, carbon dioxide, and even formaldehyde. Separate from the biosignatures, organizations on Earth are also looking and listening for technosignatures—signs of technology that a more advanced civilization may have developed that would come through the electromagnetic spectrum.

Life in Our Solar System: Venus and Mars



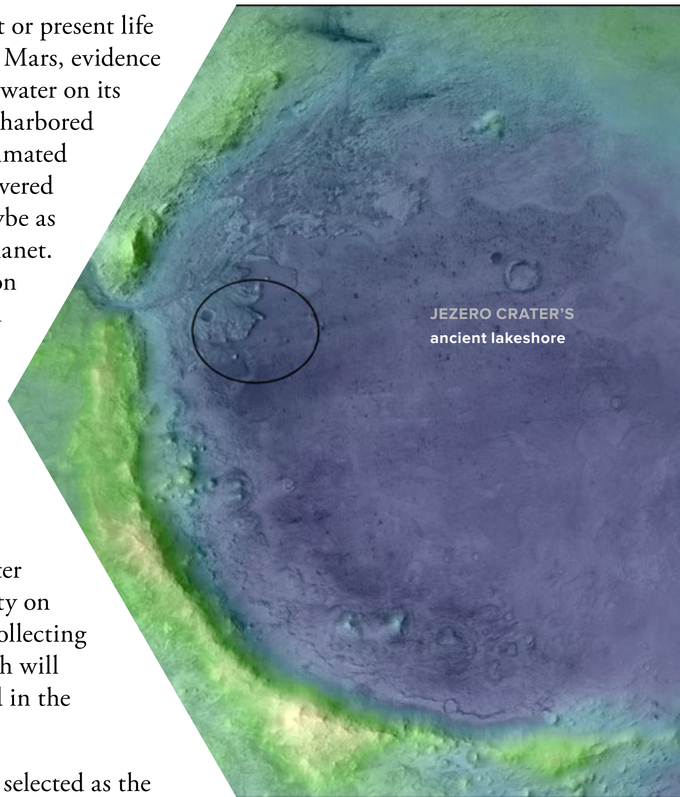
NASA's Deep Atmosphere Venus investigation of Noble gases, Chemistry and imaging (DAVINCI)

If life exists in our solar system, scientists think they might find it on a series of different planets nearby or a few moons. They're excited about the potential to find life on Venus, Mars, and the moons of Europa, Ganymede, Titan, Enceladus, and Mimas.

Although Venus is about the same size as Earth, it evolved very differently. Extreme surface temperatures of more than 500°C and atmospheric pressure more than 90 times that of Earth make it unlikely that water-based life exists or that life exists on the surface—too much pressure. However, some scientists believe that extremophile microbes might exist in the acidic atmosphere.

An upcoming mission—the Joint JPL–NASA VERITAS probe—is in development to map the surface of Venus in high resolution so as to compare it with the surface of Earth. The main mission of VERITAS is to collect data on how the geology of Venus evolved over time, find out what processes are currently at work, and ultimately determine whether water was ever present. VERITAS is expected to launch in 2031.

While no proof of past or present life has yet been found on Mars, evidence indicates it had liquid water on its surface that may have harbored life in the past. It's estimated that ancient oceans covered between 35% and maybe as much as 75% of the planet. The Mars 2020 mission included a rover called Perseverance, whose mission is to search for signs of ancient microbial life at a landing site—the Jezero Crater—that clearly shows the indications of past water and signs of habitability on the surface. It is still collecting data and images, which will hopefully be recovered in the future.



JEZERO CRATER'S
ancient lakeshore

The Jezero Crater was selected as the landing site for the Mars 2020 mission because it has a very interesting aqueous history, where scientists think there were water episodes multiple times throughout its history. So, more than 2 billion years ago, it may have been a very water-rich area where life may have emerged and thrived. In addition, the crater has a diversity of different minerals, which are key to a potentially

habitable environment, meaning they can provide the key elements and nutrients that life would have needed to thrive and also preserve signs of life for very long periods of time.

Life in Our Solar System: Three Moons

Continuing deeper into our solar system, the search for life shifts from planets to moons—and a few look promising. The first example is Europa, the smallest of the four Galilean moons of Jupiter. It has the smoothest surface of any planet or moon in the entire solar system, leading scientists to hypothesize that a liquid water ocean is beneath the surface. Life could exist in Europa's ocean, similar to the way that life can be found near hydrothermal vents on Earth.

Jupiter's moon
EUROPA

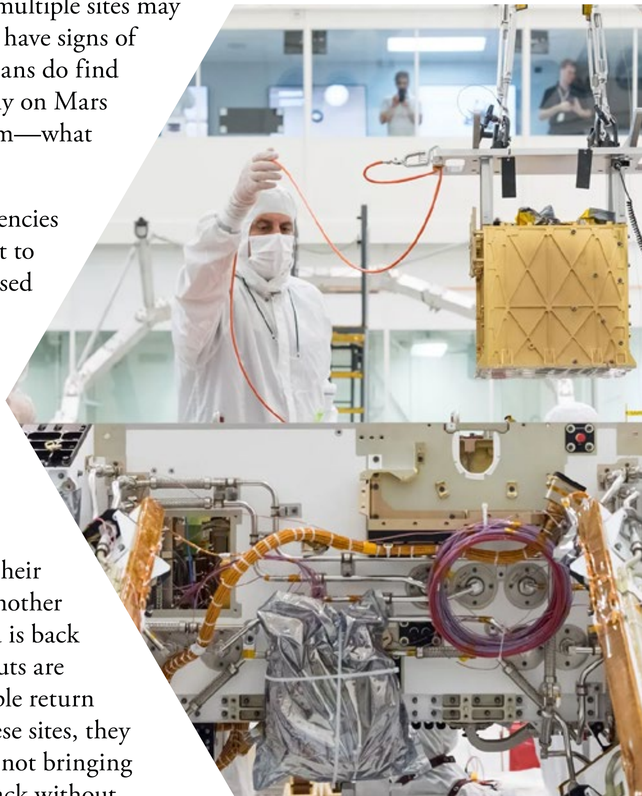
The second moon where life might be found—Ganymede—also orbits Jupiter. It is the largest moon in our solar system, and the Hubble Space Telescope has found evidence of a large subsurface saltwater ocean that holds more water than all of Earth's oceans. Ganymede is the only moon in the solar system to have its own magnetic field, and evidence shows that a thin oxygen atmosphere probably formed from its icy surface.

The final example is the moon of Titan, the largest moon of Saturn. It is shielded from the solar wind by Saturn's magnetosphere around 95% of the time, and its surface temperature is around –180°C. It is the only moon known

to have a dense atmosphere, which is mostly nitrogen and methane. Other than Earth, it is also the only body known to have a surface liquid—in this case, methane seas, lakes, and rivers—with possible subsurface liquid water. On Titan, liquid mixes may provide prebiotic chemistry for living cells different from those on Earth.

The Ethics of Finding Life

Within our solar system, multiple sites may either harbor life or could have signs of past life. However, if humans do find evidence of life—especially on Mars but also in our solar system—what should they do?



NASA and other space agencies have given a lot of thought to this and have already devised protocols for planetary protection, the goal of which is to prevent two different types of contamination. The first is forward contamination, where astronauts need to make sure they're not bringing their own human material to another celestial body. The second is back contamination. If astronauts are ultimately able to do sample return missions from some of these sites, they need to make sure they're not bringing extraterrestrial material back without quarantining it or first understanding the influence it might have on our own world.

To address some of these challenges—and to make sure that humans are acting ethically and responsibly—the Committee on Space Research comprises more than 2,000 scientists who meet every 2 years to review protection protocols. As of now, there are five categories of mission types based on whether chemical evolution or the origin of life may be present: no planetary protection required; minimal protection required; flyby missions; sterilization; and restricted or unrestricted sample return.

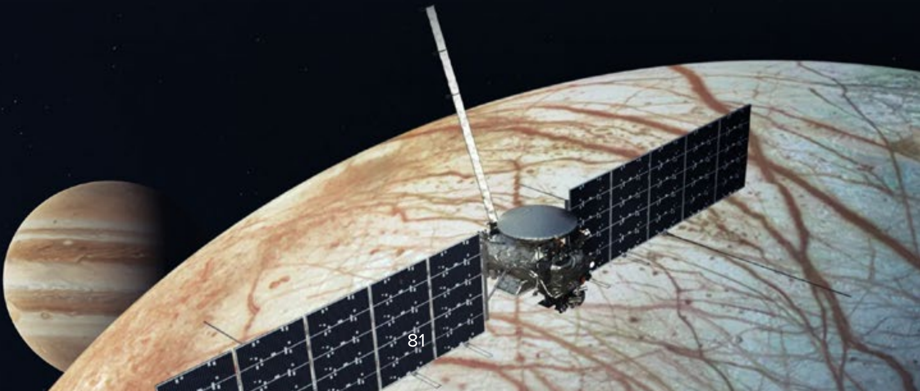
Within this context, there's an absolute prohibition of destructive impact on Earth. So, if any reason exists for believing that gathering these samples would endanger life on Earth, we would not bring them back or allow that mission to go forward without extreme precaution—and containment of all returned hardware and samples.

Finding evidence of life elsewhere in our solar system or on an exoplanet would be the most exciting discovery in human history and would gratify the thousands of people who have worked throughout the space industry and in other fields to answer some of our most fundamental questions.

12

The New Ethical Problems of Space

NE OF THE INSPIRING THINGS ABOUT SPACE IS THAT it takes people out of their everyday perspective and encourages them to think in broader terms. For example, people who have experienced the overview effect report an increased sense of connection—not only to other people on Earth but also to Earth as a whole. In this final episode, you'll explore how a future in space could impact human values and perspectives. What responsibility do humans have to Earth as they start to live in space and on other worlds? What new freedoms might they gain, and what new constraints could they face?



Changing Perspectives in Space

If life on another world should be protected from potential harm, yet we do not often give the same consideration to life on Earth—from microbes to the most developed animals and plants—then how do we justify such a difference in treatment? In this sense, one value of space ethics is that it could shift our ethical considerations away from being centered on just human values and concerns toward an ethics that incorporates a much broader range of issues.

Another way space changes our perspective is with how we interact with each other. One might think that the close quarters on the ISS or future habitats on the Moon and Mars would elicit frayed nerves and a desire to be alone. However, evidence from the Astronaut Ethnography Project reveals that there's a community aspect to space in which people tend to look out for each other. Crews are also very good at using humor and communication to try to work through what they are experiencing and care for one another.

In some sense, space seems like the ultimate liberating experience. Being in microgravity frees people to move and act in ways that they could never do on Earth. But living in space would also introduce new constraints.

For example, once you touch any part of the lunar surface, you can never make it look untouched. However, there may come a time when communities are living on the Moon, and the opportunity to look at or contemplate unruined native lunar terrain might have some kind of psychologically restorative value. If people don't protect any of it, once it's gone, it'll be gone forever.

In space, people would live in an environment where the lives of so many continually hinge on the good actions of every one of them. So, there would be a need to think about what type of society could handle that risk. In a world in which individual freedom may result in the instant devastation of a community or the deaths of many people, it would force people to rethink what individual freedom means in a social environment.

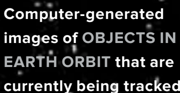
These issues are important for humanity to consider since they will undoubtedly impact how future space laws are written and adjudicated and what forms of governance space stations and colonies may have.

APOLLO 16
LM Orion

However, some laws and agreements are already in place. The most significant is the Outer Space Treaty, which all major spacefaring nations have adopted. It lays out the rules for the peaceful exploration of space and forbids any country from claiming sovereignty in space or over any celestial body. Importantly, it also prohibits the establishment of military bases, testing weapons, and military maneuvers on the Moon and celestial bodies.

Space Debris

Another area of space ethics that is getting increasing attention is our obligations toward space debris. There are millions of pieces of space debris in LEO, ranging from large pieces like spent satellites and rocket boosters to small pieces only centimeters in size. Much like on Earth, we are responsible for the safe disposal of waste so that we do not pollute the space environment. In addition, since all of these pieces are orbiting at speeds of around 29,000 kilometers per hour, even the smallest particles can severely damage space stations, satellites, and other assets, potentially putting lives at risk.



Computer-generated images of OBJECTS IN EARTH ORBIT that are currently being tracked

The possible solution for solving this debris problem is twofold. First, if each piece of a space station were its own spacecraft, it could navigate its way through space. Second, when it came to the end of its life, its reentry could be controlled to make sure it didn’t become a new part of the space debris problem.

In addition, scientists are looking to develop new technologies that can be used to either remove space debris or perhaps even recover and recycle it for new things in space.

While the main way to dispose of debris is de-orbiting, this process has at least two effects. As the debris burns up, it not only warms the atmosphere but also releases chemicals that can contribute to ozone depletion. Larger pieces of debris that do not fully disintegrate reach Earth and must, therefore, be directed to uninhabited areas—usually the ocean. While this is unlikely to harm humans, it does pollute the sea. With this in mind, we must make sure to treat Earth with respect and be fundamentally responsible actors when it comes to limiting and mitigating space debris.

Values in Space

Space can be a tool for transformation—a way for humanity to grow and aspire to new heights. So, what kinds of lives might we want to lead in space? Researchers at MIT have proposed four values that might motivate the foundation of a spacefaring society.

The first value is the freedom to move—preserving humans' right to always come home or move between future settlements. The second is freedom from fear. Space can be a dangerous place, so making sure we are truly valuing and respecting human life is important.

The next value is the freedom to create, which relates to self-expression and the ability to create new models for self-governance as settlements expand. The last value is freedom from oppression. In this next era of human spaceflight, people should have the freedom to move beyond some of the past fraught activities of humanity, try not to repeat the wrongs of colonialization, and bring us into a brighter future—balancing the utopian ideals that often accompany the idea of space exploration with the pragmatism of keeping people alive and treating people well.

The Future of Space in 20 to 50 Years

In 20 years, there will be an emerging space tourism industry that will enable a much broader demographic of individuals from many nations across the world to go to space, experience a lunar flyby, or perhaps even stay on the surface of the Moon for 2 or 3 weeks at a time. The lunar surface may have structures that are a little more permanent. People will make more trips to the Moon and do a lot more exploring there. In addition, we might be extracting ice and water from the Moon and making fuel on the lunar surface to take us to Mars.

We'll be planning for Mars missions during this time, but it's doubtful they will be underway. There is still much we don't know about the risks relative to human health when it comes to Mars transit and taking on the challenges of transportation for a Mars mission.

In 20 years, there could be tens, if not hundreds, of people living and working regularly off the planet—but doing so not because they're just there but because there are economic reasons to be there. They're in space manufacturing applications, and research opportunities and labs are operating. A whole swath of infrastructure and logistics projects are being done in space that warrant and drive the need to have human hands and human capability in orbit to execute all of that.

In the next 20 to 50 years, humans will be working and living in LEO, and the idea of doing so will seem several notches less risky and unusual than it does today. There will be a lot of commercial activity, which might be readily

accessible science stations that academics could go and visit or space hotels where tourists can go up into space, experience life there, get that overview effect where they see Earth from space, and then come back down to Earth.

In the next 50 years, more permanent habitats will exist on the Moon. For example, scientists and researchers may go for a 5-year stint and become immersed in lunar research. A little more tourism will also go to the Moon. However, it's doubtful that there will be anything completely permanent, such as a city on the Moon, within this time.

Finally, in the next 50 years, humans will have made it out to Mars, have gone and done some research there, and may even have a significant population on the planet. As a result, we'll also have learned a lot more about Mars, and we may be in Europa and even deeper into space.

The Future of Space in 50 to 100 Years

As we evolve into the 50- and 100-year time frame, a layered infrastructure will develop in LEO to ultimately become the jump-off point for future and deeper exploration in the solar system. Missions will no longer leave from Earth to go to another planet or the Moon. Instead, humans and equipment will leave the planet, go to LEO—where spacecraft are perhaps being built—and then go further and further into the solar system from there.

So, there may be thousands or millions of people in LEO, which will become the next frontier for exploring deep space—like sailing across the seas and oceans. In terms of manufacturing and infrastructure, some of those things that people don't want on Earth could be put in LEO, which could improve life here on Earth.

In addition, 100 years from now, humans may have self-sustaining settlements on both the Moon and Mars. Certainly, temporary research will be set up on the Martian surface, and the Moon will be more established. In addition, we'll have more probes going to deep space—perhaps to the moons of

Jupiter—as we learn to be independent in space through living on the Moon and Mars. In this regard, we could have actual off-Earth habitats that are sustained over long periods of time.

Earth is changing in a very drastic way right now. Certain places on the planet are becoming so extreme in terms of environment that it's driving people to leave those areas. So, if we can make Earth more livable for more people in the next 50 to 100 years and there can be more access to clean land and fresh water, that would be a success for humanity. This idea can be understood as the flip side of the coin to space exploration—as we're looking out, we need to continue looking in and improve the conditions on Earth.

Thinking 1000 years out, humans could have left the solar system and be exploring new worlds, just like the science fiction authors have always dreamed about.

Humanity is at an important juncture right now—at the cusp of its next metamorphosis into a spacefaring species. In this modern era, we are developing and leveraging more and more technologies that give us incredible agency at a planetary scale. We have the responsibility to protect and preserve our home planet; at the same time, we will have the capability to expand beyond Earth and push our boundaries like never before. We can achieve both objectives and elevate the lives of everyone as we do so. Humanity is at its best when people are striving to reach distant but attainable goals. Space exploration is just that—striving to bring to life a visionary, aspirational future that can be accessed by all.

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