UPWARD®

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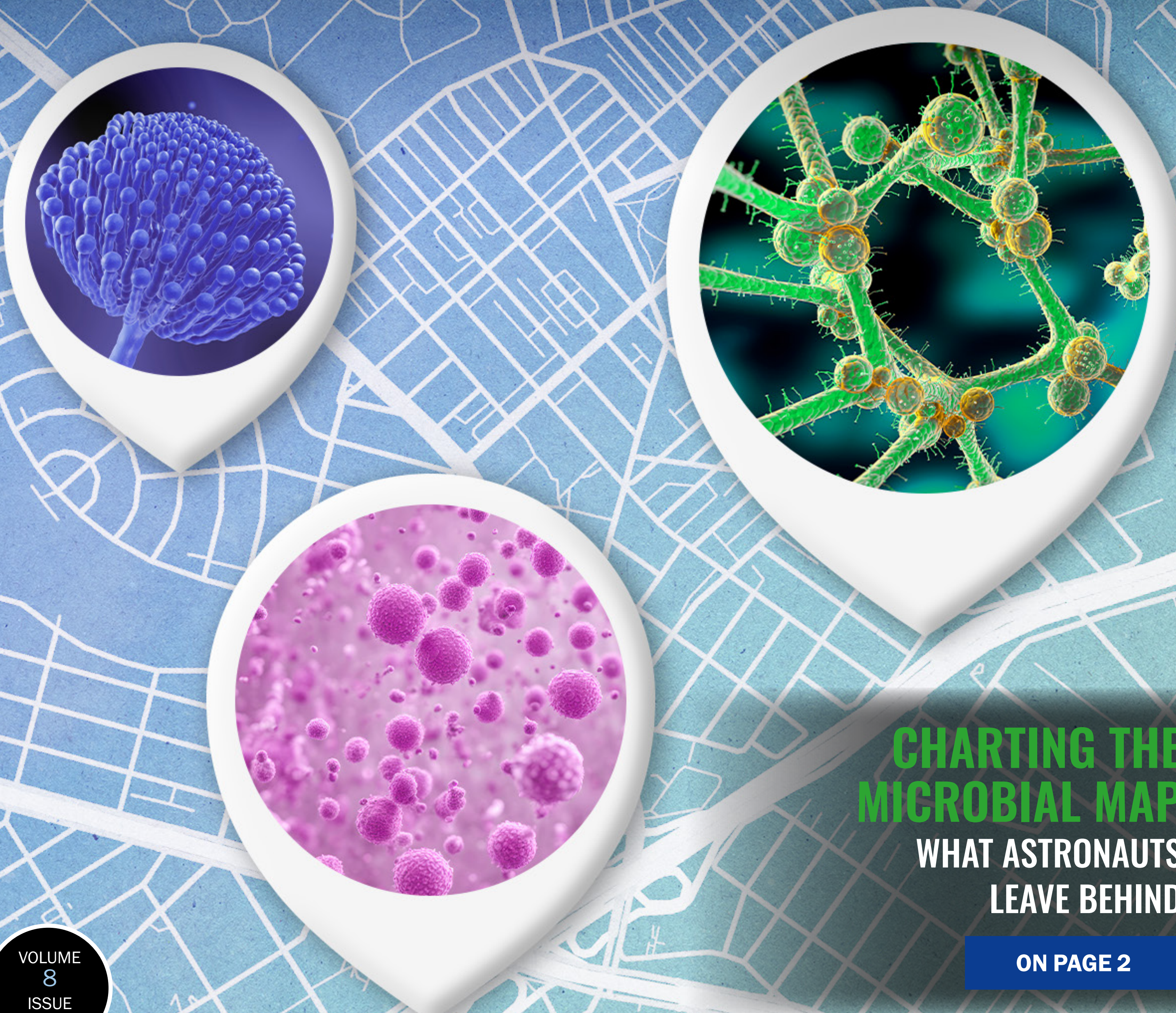


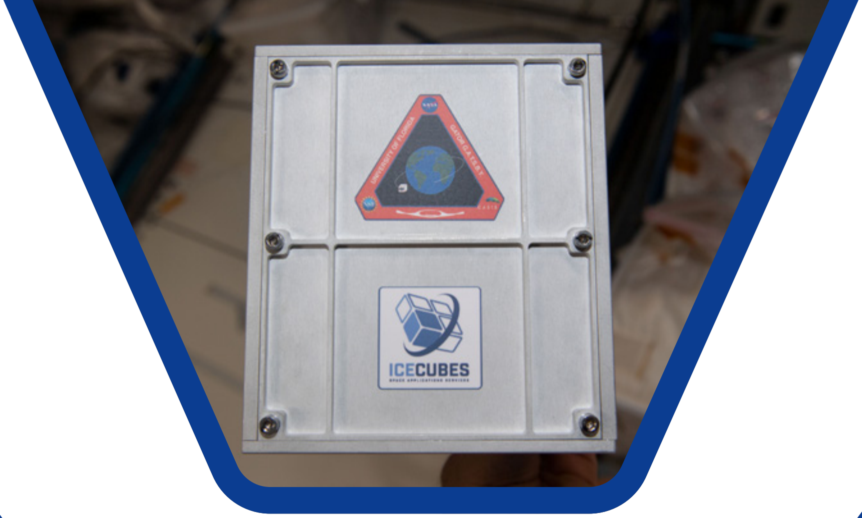
CHARTING THE MICROBIAL MAP

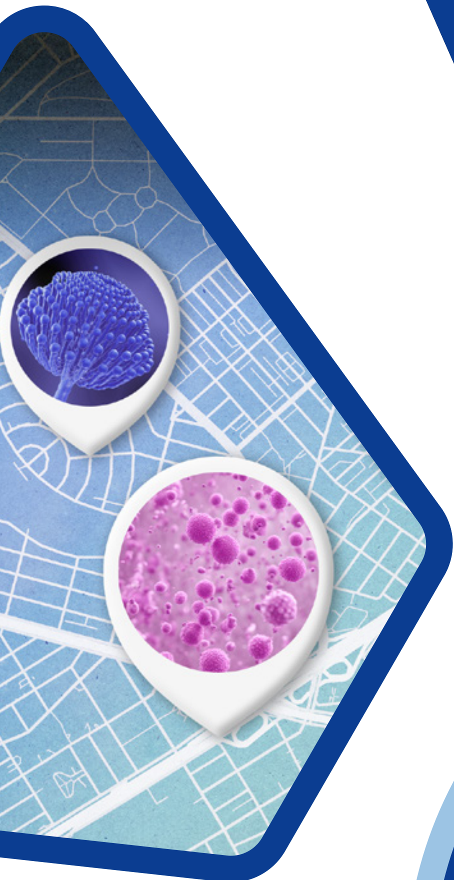
WHAT ASTRONAUTS LEAVE BEHIND

ON PAGE 2

VOLUME 8
ISSUE 3

ISS NATIONAL LABORATORY®
CENTER FOR THE ADVANCEMENT OF SCIENCE IN SPACE®





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VIEW FROM THE CUPOLA

By Sachin Velankar | NSF Program Director

Sachin Velankar is a Professor in Engineering at the University of Pittsburgh and a rotating Program Director at the National Science Foundation.

Up. That's where hot air rises and bubbles float. Down. That's where everything falls—but not in space.

Objects float aimlessly, and fluids are even less predictable. Liquid drops may bounce off surfaces, break into smaller droplets, spontaneously accumulate in corners, or remain beaded up. How to manipulate fluids that don't go where expected has been a NASA focus for as long as there has been a space program. In space, bubbles can block fuel lines because liquid fuel does not drain downward, and fires may spread in unexpected directions because hot air does not rise upward.

But the lack of gravity also offers unrivaled opportunities to investigate fluid flow phenomena that would simply not be possible on Earth. Almost a decade ago, the U.S. National Science Foundation (NSF) partnered with the Center for the Advancement of Science in Space® (CASIS®) to provide researchers with access to the only national laboratory in space. Since then, NSF has committed more than $46 million to space-based research across the physical and life sciences and has supported more than 70 ISS National Lab-sponsored projects. On the ground, researchers could not observe the phenomena of interest because gravity would dominate and altogether suppress them. This Upward issue highlights some of the research supported by NSF through this partnership.

In one article, a University of California, Santa Barbara team uses light to drive bubble motion. This NSF-funded research exploits Marangoni flow, a phenomenon seen at a kitchen sink: sprinkle soap (a surfactant) into dirty dishwater, and the debris will move outward from the drops. This is because the surfactant reduces surface tension, causing an imbalance in force at the surface. The team designed photosensitive surfactant molecules that reshape almost instantly under light, altering surface tension and propelling bubbles. On Earth, buoyancy overwhelms such subtle forces, so microgravity is essential to see the movement. This research opens paths toward microscale heat transfer in electronics and precise fluid control in space systems.

The topic of another article can also be seen in the kitchen: when a wet finger circles the rim of a wine glass, the glass sings due to the vibrations. But if the glass is partly filled with water, these vibrations cause waves on the surface. A University of Florida team examined such Faraday waves on the ISS in an NSF-funded investigation. On Earth, Faraday waves are affected by gravity and surface tension. But in microgravity, they are completely different, opening avenues for applications like rapid heat transfer. The team, along with Japanese collaborators, also leveraged the ISS to observe waves on the surface of molten metal drops to measure surface tension, which is important for applications like 3D printing of metals and precision soldering.

In the cover story, we turn from inanimate bubbles and fluids to microorganisms. Although not funded by NSF, a project from the University of California, San Diego and NASA's Jet Propulsion Lab provided valuable insights into microbes in space. We imagine the ISS as an immaculate environment, and NASA takes elaborate precautions to sterilize everything before launch. But myriad microorganisms stow away on astronauts and colonize all corners of the ISS. The team is mapping this microbial community to understand how life adapts in space. Some adaptations include antibiotic resistance, which raises concerns. Will microbes pose a risk to astronauts on long-duration missions?

I grew up an avid fan of science fiction, most of it related to space travel (shout-out to Arthur C. Clarke). So I have been excited and privileged to participate in this NSF-CASIS partnership for the last two years. Many of my fellow NSF Program Directors have been involved for several years, and working with our CASIS colleagues to evaluate the amazing research proposals is an annual highlight. It's thrilling to learn how scientists can leverage microgravity to test fluid flow theories, measure fluid properties, and fabricate new materials.

NSF's mission is to advance scientific progress, and one way we do this is by providing research infrastructure beyond the capabilities of a single investigator or institution. The NSF-CASIS partnership represents the ultimate example of exceptional infrastructure—a laboratory that is, quite literally, beyond this world.

Charting the Microbial Map

What Astronauts Leave Behind

By Stephenie Livingston,
Staff Writer

Astronauts have company on the International Space Station (ISS). Bacteria squat on handrails. Skin flakes lodge in air vents like lint. A corn-loving fungus has become a regular. The place looks spotless, but it's crawling—its surfaces inscribed with cells and spores.

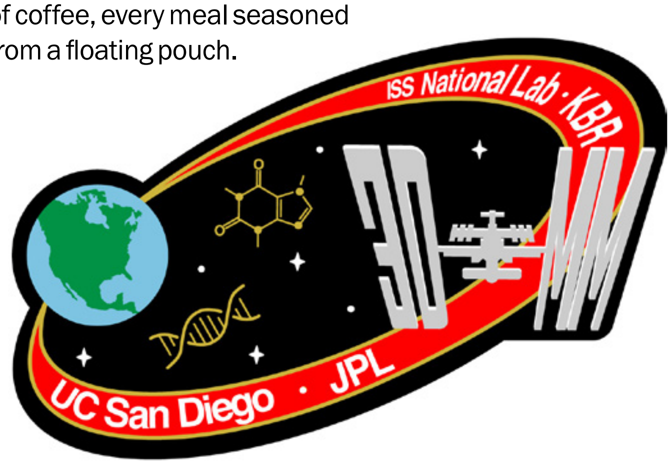
Scientists want the census, and that's how Nina Zhao found herself opening swabs from the space station. She wasn't expecting pepper grains, or bread mold, either, for that matter. Zhao, a postdoctoral scientist at the University of California, San Diego (UCSD), specialized in mass spectrometry, not space exploration. Yet, she and Rodolfo Salido, a Ph.D. student also at UCSD, found themselves poring over hundreds of cotton tips that had been swept across walls, toilets, and table edges by astronauts, then shipped back to Earth, like evidence from a crime scene.

To make sense of them, they relied on untargeted mass spectrometry, a tool that scans everything at once. It plots molecules as jagged peaks, showing the chemical fingerprints of whatever clung to the ISS surfaces. Matching those patterns against vast databases slowly resolved the peaks into recognizable shapes: caffeine, skin bacteria, bread mold, a pathogen or three.

"Basically, things stay on the surface," says Zhao, a finding she found surprising. "We were still able to see the impact of human activity on the surface chemistry of the space station, even under the zero gravity conditions. It's an incredible example of the resiliency and complexity of microbial life."

The samples were part of a decade-long ISS microbial survey led by Kasthuri Venkateswaran at NASA's Jet Propulsion Laboratory (JPL). An ISS National Laboratory®–sponsored investigation scaled up the project: astronauts swabbed 803 surfaces across nine modules. Using chemical and genetic profiling, researchers at UCSD and JPL built the first 3D microbial and chemical map of how humans and microbes coexist in space onboard the U.S. Orbital Segment. Published in Cell, the study showed for the first time on this scale that microbes and molecules drifted not chaotically, but in ordered, location-specific patterns, much like in homes on Earth.

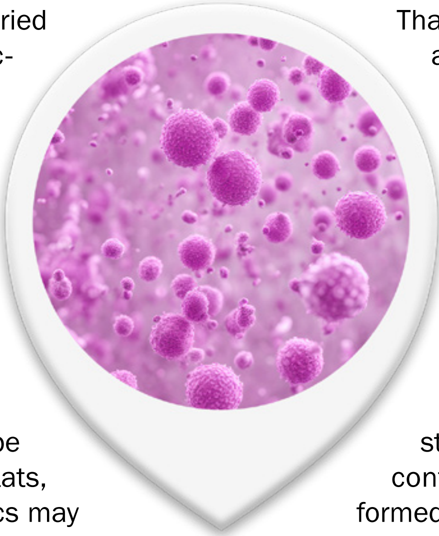
In the ISS galley, Zhao's instruments detected evidence of food and drinks. In the restroom, she found the chemical signatures of human metabolites. And like the rest of us, astronauts are prolific shedders—walking fermenters whose skin alone contributes 80 percent of the microbes onboard. The station's microbiome records it all: every routine, every sip of coffee, every meal seasoned from a floating pouch.



Mission patch for the Three-Dimensional Microbial Mapping (3DMM) project, which maps the microbial and chemical environment on the ISS in unprecedented detail.

Nina Zhao

Along those traces, some pathogens carried unusually heavy loads of antibiotic-resistance genes, while many chemical signals remain unidentified, evidence that the ISS holds a microbial frontier.



“Your microbiome comes with you whether you want it or not,” says University of Florida space biologist Jamie Foster, who studies how microbes behave in extreme environments. She wasn’t involved in the investigation, but notes that findings like these could shape the design of future Moon or Mars habitats, where understanding microbial dynamics may prove essential to survival.

Surprising Passengers

Using molecular sequences, Venkateswaran’s lab has described more than a hundred new bacterial species, from NASA cleanrooms where space missions are built to the ISS. One hardy specimen shrugged off extreme radiation. Another, found on station, now bears retired NASA astronaut Kate Rubins’ name after she helped expand the investigation.

NASA astronaut Kate Rubins prepares surface-sampling kits for the most detailed microbial and chemical map of the ISS to date.

NASA

That hunt for hidden passengers continues a long tradition. All spacefaring nations have worried about contamination since the dawn of interplanetary exploration. In fact, the 1967 Outer Space Treaty obliges nations to avoid “forward contamination” of other worlds to prevent compromising the search for life. To meet that obligation, NASA baked the 1970s Viking landers at 233 °F for 30 hours—essentially putting two spacecraft in an oven—to kill microbial stowaways. On the Russian Mir station, by contrast, biofilms had grown so thick they formed dripping “bio-globs” on the walls.

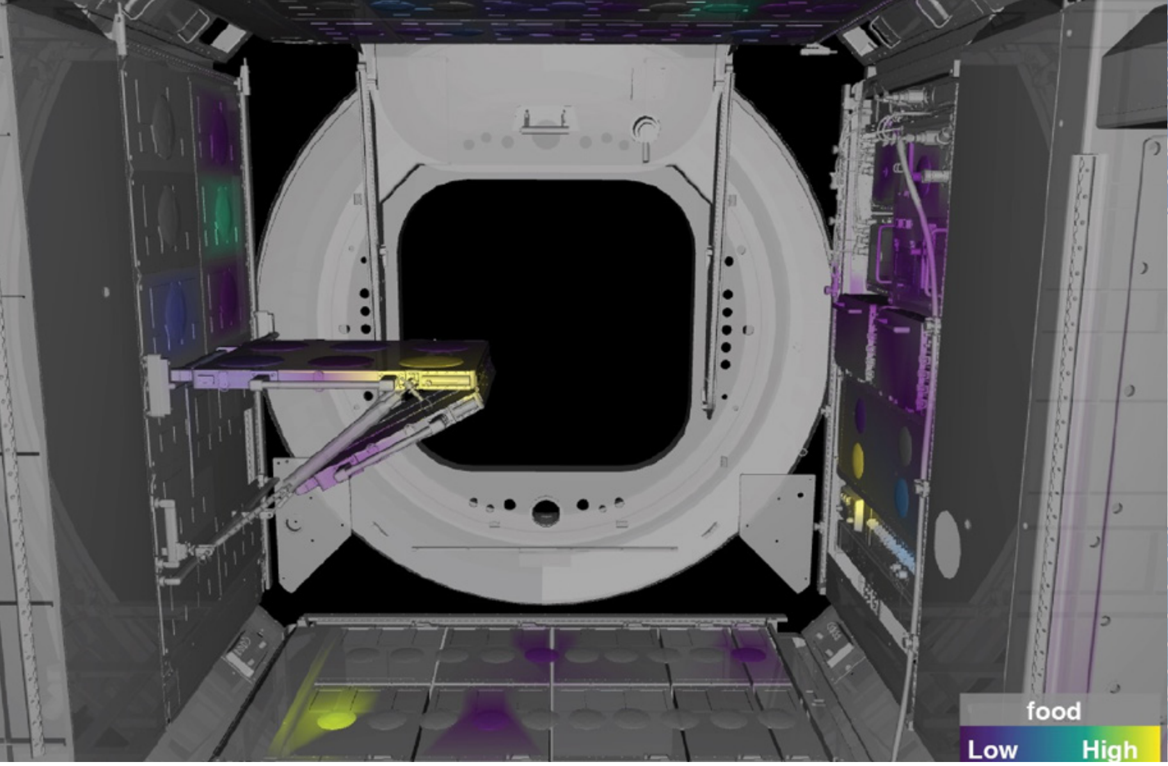
Venkateswaran calls the ISS investigation the next chapter in that history, akin to a forensic investigation. Researchers used two powerful techniques—untargeted metabolomics and genetic sequencing—to build the microbial map. The sequencing looked at all genes, as well as specific ones like 16S rRNA, a kind of molecular clock that helps scientists trace how organisms evolve and relate to one another. And like any good forensic case, it had its share of surprises.

In an earlier investigation, Venkateswaran and his team had discovered one hitchhiker, *Pantoea pearsonii*, clinging stubbornly to a surface inside the ISS. On Earth, the bacterium had previously been misidentified or labeled an emerging pathogen, but the team was able to fully characterize it from their ISS sample. Found in hospitals, it is resistant to frontline antibiotics, causing septicemia, kidney stones, and weeks of illness. It resurfaced on the space station in 2022 during the team’s ISS National Lab investigation.

“We haven’t been able to clean it up,” Venkateswaran says.

The microbes living on the ISS come from Earth, but adapting to space pushes them in new directions. Under radiation, microgravity, and confinement, some strains accumulate unique traits. A few have even diverged enough to classify as new species.

Among others cataloged from the ISS were six pathogens on the World Health Organization’s “ESKAPE list,” a roster of organisms notorious for causing hospital outbreaks. *Klebsiella pneumoniae* was there, known for causing respiratory infections. *Pseudomonas*, was there too, a slippery organism capable of thriving on minimal nutrients. And all of them, when compared to their Earthly counterparts, carried an unnerving number of resistance genes, particularly against the beta-lactam antibiotics that hospitals rely on.



This visualization of the ISS Node 1 module shows where food-associated microbes accumulate during daily life in orbit, with analysis tracing each microbial signature to likely sources, such as food, crew, and equipment.

Research Team

"I was surprised there were all these ESKAPE pathogens and viruses," Foster said. "So there has to be a lot of monitoring to make sure good bacteria aren't going bad."

Scientists think those genes accumulate for a reason. Life on the ISS is harsh. Bacteria are constantly bathed in disinfectants, exposed to radiation, and forced into close quarters where they jostle against one another. Under that kind of pressure, microbes either adapt or die, and the adaptations that help them survive often involve genes that also blunt the effect of antibiotics.

Similar patterns appear in other sealed, human-dominated environments on Earth—surgical suites, hospital wards, even aerospace cleanrooms—where limited contact with the outdoors creates selective pressures like those on the space station. The ISS is a particularly unique example, but not an exception: once bacteria pick up those defenses in any such ecosystem, they have every chance to pass them along.

The chemical side of the study, however, carried more mysteries.

"Most of the recovered metabolites were unknown. They just have no idea what they are," Foster said. "So many are black boxes, so to speak, or gaps in knowledge representing a challenge for us to understand." Even among the metabolites documented in the study, a large portion could only be guessed at or flagged as "lipids" or "peptides" with little else to go on.

But the ISS is not a cesspool. It's cleaner than most homes, just not as sterile as an intensive care unit. And that's a good thing.

"If it's too sterile, even minor pathogens become dangerous," says Venkateswaran. "You need good microbes to balance the bad ones." Foster agreed: in space, as on Earth, the goal isn't minimizing microbes but fostering diversity, she says.

Venkateswaran once tried to persuade his Russian colleagues to collect samples from their half of the station, since he wanted to compare the microbial diversity of the two segments.

"The excuse was, 'We don't want to know,'" he recalled, amused. He noted that this attitude highlighted the culturally loaded nature of the truth that wherever people go, microbes follow.

Looking Ahead with Microbes in Mind

The persistence of pathogens like *Pantoea pearsonii* raises concerns for astronaut health, especially on long-duration missions to the Moon or Mars where evacuation is impossible. To mitigate risk, researchers are already thinking about how spacecraft and habitats might be designed with microbes in mind.

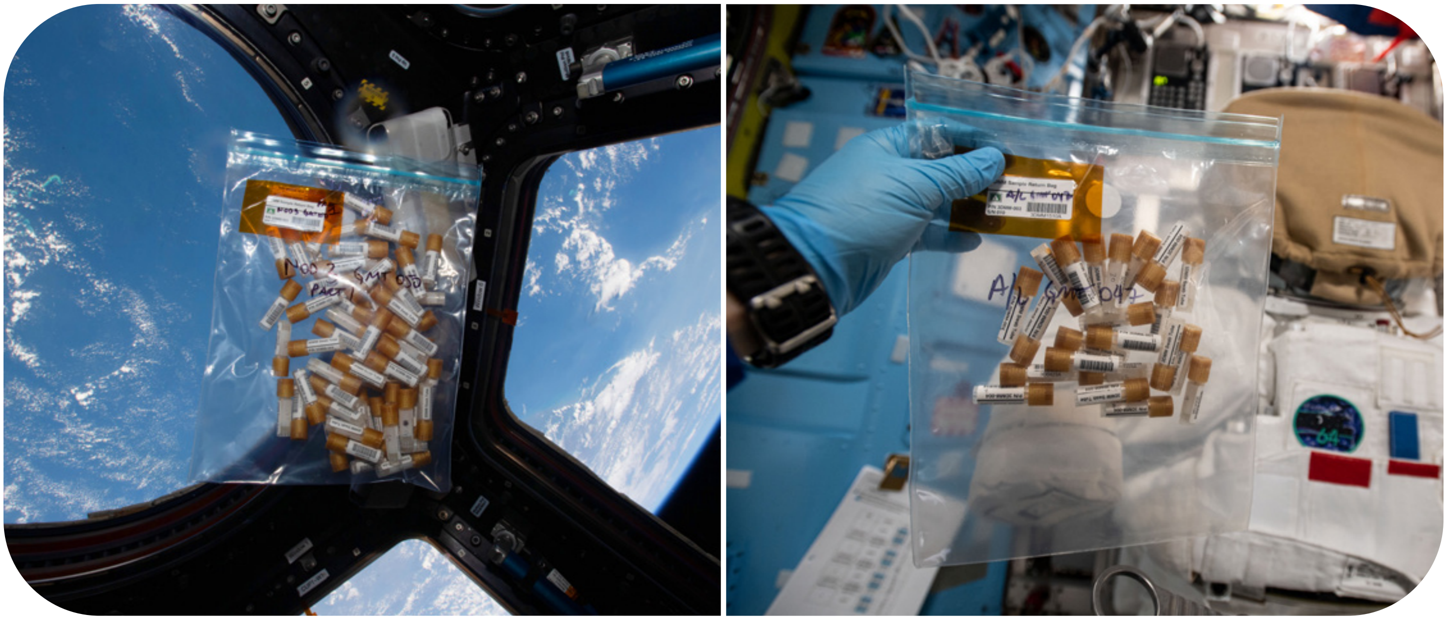
Standard DNA sequencing is too cumbersome for everyday diagnostics in space, so researchers are exploring alternatives. One idea is biosensors: instead of sequencing DNA, they would detect the chemical metabolites microbes emit, using miniaturized mass spectrometers already adapted for orbit. Venkateswaran envisions them working "like a smoke alarm," alerting astronauts when a pathogen breaches the threshold. The same technology might one day monitor hospitals and schools for outbreaks.

For Zhao, the biggest surprise was the orderly patterns. Microbes didn't drift chaotically but recorded the station's routines. That consistency, she says, could guide the design of sensors and habitats alike, allowing layouts that limit spillover, airflow that prevents buildup in vents, and surfaces engineered to resist colonization.

Venkateswaran jokes that microbes will be the first true settlers of space. They travel light and thrive where we least expect them. Foster recognizes the stakes in that idea: on the Moon or Mars, the wrong infection could mean life or death. There's no ambulance, no quick trip home. The ISS is a safeguard, she says, and remains our best testing ground for understanding long-term microbial behavior in space.

"It's a fantastic resource for scientists. I hope we can find a way to keep it as long as possible, as this science is hitting its stride," she said.

To Zhao, the ISS isn't a sterile lab but a deeply human place, recorded in nearly a thousand microscopic fingerprints. Bacteria on surfaces, crumbs from space snacks, skin flakes sifting through recycled air. Every smear reminds us that wherever we go, microbes go, too. They don't just cling to us, they map where we've been, and it will take understanding them to build a home off world.



The sampling tools used to swab surfaces across the ISS for the study.

NASA

Good Vibrations

Transforming Cooling and 3D Printing in Space

By Amelia Williamson Smith, *Managing Editor*

The ICECUBES hardware on the ISS housing the team's four fluids containers and shaking system.

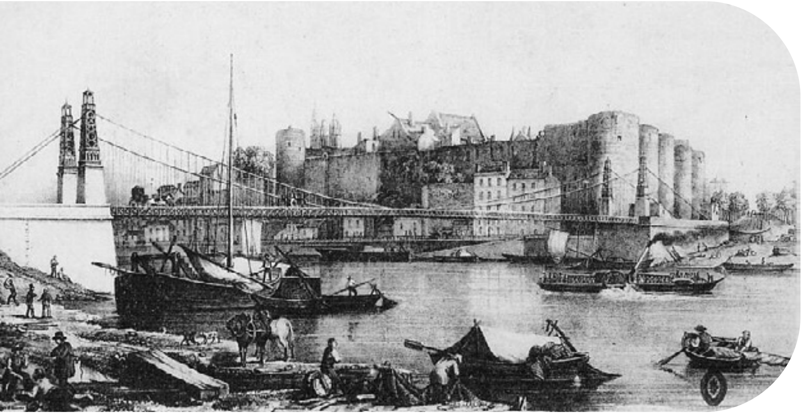
Aerospace Applications North America

It was a dark and cloudy April morning in 1850 near Angers, France. Three battalions of French soldiers approached the Basse-Chaîne Bridge, which provided passage over the Maine River. Just as the third battalion stepped on the bridge, a fierce storm broke out.

As the nearly 500 soldiers marched across, the large suspension bridge began to sway in the gusting wind. Despite the driving rain, the soldiers continued to march in unison, their boots coming down in a rhythmic thud. When they reached the middle of the bridge, suddenly, there was a loud snap. The bridge gave way, and the soldiers were thrown into the raging river beneath. More than 220 people died in the tragic event.

The culprit for this disaster was resonance. When a system is vibrated at a frequency matching its natural frequency, it creates resonance, which amplifies the system's oscillations. To understand natural frequency, picture what happens if you bump a plate of Jell-O. The Jell-O jiggles, or oscillates, back and forth before eventually coming to rest. The frequency of those oscillations is the natural frequency. In the case of the soldiers, the vibration from their marching matched the natural frequency of the suspension bridge, amplifying the oscillations until the bridge violently broke apart.

The power of resonance can be destructive, but a team of scientists at the University of Florida (UF) aims to harness it for something good. They want to use resonance to address an important challenge in space: heat removal.



The Basse-Chaîne Bridge prior to its collapse in April of 1850.

Wikimedia Commons

The University of Florida team at Kennedy Space Center preparing its ISS National Lab-sponsored and NSF-funded investigation for launch. (left to right: Craig Singiser, Zach Karpinski, Jason Livesay, Ranga Narayanan)

Aerospace Applications North America

"We will need thermal management when we inhabit the Moon and Mars," said UF distinguished professor Ranga Narayanan. "We'll have energy sources like nuclear reactors, and we're going to have to remove the heat from the system quickly."

On Earth, passive liquid cooling transfers heat out of systems using natural convective currents. But in space, there's a complication.

"If there's no gravity, you don't have fluid naturally flowing from high density to low density, forming convective cycles, which is a key heat transfer mechanism on the ground," explained Thomas Corbin, a Ph.D. student in Narayanan's lab. "Resonance is a way we can circumvent this issue by inducing flow."

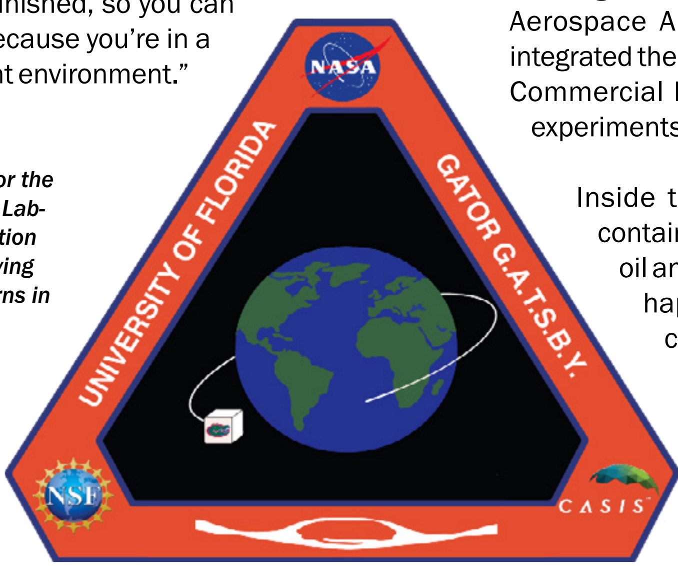
Portrait of Michael Faraday.

iStock

When a liquid is vibrated at the precise frequency to create resonance, a pattern of waves forms, causing the liquid to flow. However, to design heat removal technology based on resonance, researchers must fully understand the dynamics of how and why the fluid moves. Surface tension is a key part of that, but it's hard to study on Earth because gravity is too strong and overpowers it.

The research team needed a way to remove gravity, and the International Space Station (ISS) National Laboratory provided the perfect platform.

"There are a number of things that can be learned when you exclude the effects of gravity," Corbin said. "You have a force that plays a massive role on Earth that is suddenly very diminished, so you can get new science because you're in a completely different environment."



The mission patch for the team's ISS National Lab-sponsored investigation funded by NSF studying Faraday wave patterns in microgravity.

University of Florida

Faraday and His Violin

In the early 1830s, English physicist and chemist Michael Faraday was intrigued by how vibrations affect materials. Building on the work of earlier scientists like Ernst Chladni, Faraday conducted experiments using a sand-covered metal plate and a violin bow. When he slid the bow along the edge of the metal plate, the sand formed into geometric patterns, a striking visualization of resonance.

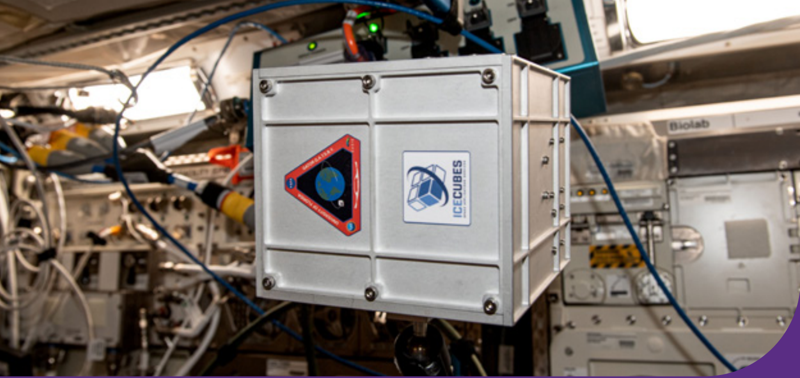
Faraday pushed his vibration studies further and designed an experiment to vertically shake a shallow container of liquid. When the amplitude and frequency of the shaking were low, the liquid's surface remained flat. As the frequency increased, the system reached a critical threshold where the surface became unstable and formed a pattern of standing waves. This phenomenon is known as Faraday instability.

Now, nearly two centuries later, the UF research team is building on Faraday's curiosity—in space. As part of a project funded by the U.S. National Science Foundation (NSF) and sponsored by the ISS National Lab, the team designed a system to vertically shake fluids to see how they behave in microgravity. The system had to be compact: less than seven pounds and able to fit in a box smaller than a toaster.

Narayanan and his team—which included Corbin, Ph.D. student Jason Livesay, and undergraduates Craig Singiser and Zach Karpinski—3D printed the components for the system and had them machined. The team then began working with ISS National Lab Implementation Partner Aerospace Applications North America (AANA). They integrated the parts into one of the company's International Commercial Experiment Cubes (ICE Cubes) that hosts experiments on the ISS.

Inside the ICE Cubes hardware were four small containers. Each held two fluids that do not mix, like oil and water. The researchers wanted to see what happened at the line where the liquids meet, called the interface, when they vibrated the containers.

The team had created theoretical models of the fluid flow, but Narayanan wondered, "Will we see the interface begin to deflect in space the way we expect it to?"

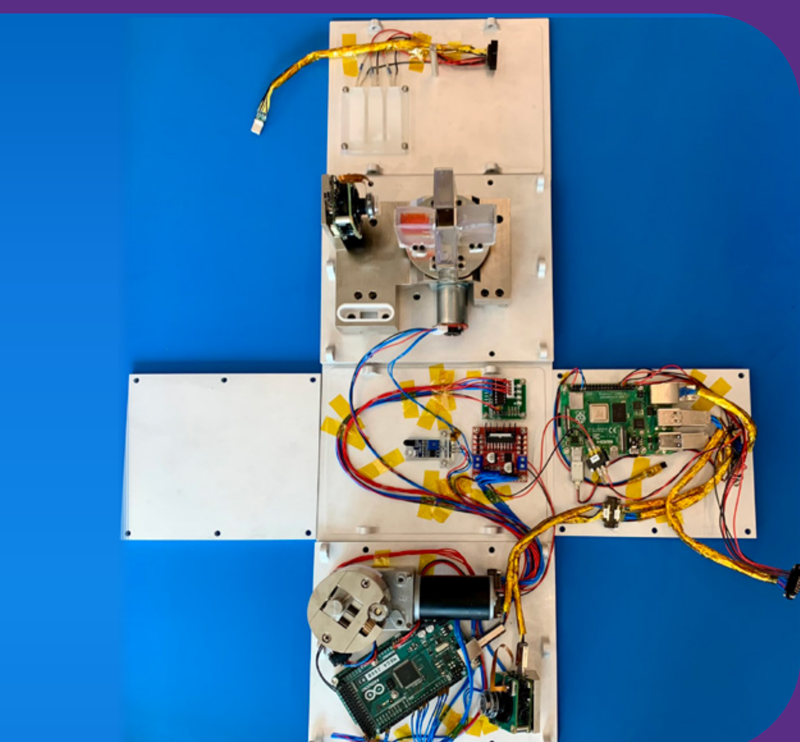


(Above) The ICECUBES hardware on the ISS housing the team's four fluids containers and shaking system.

Aerospace Applications North America

(Above) A container holding two fluids is shaken vertically on the ISS to study the Faraday wave patterns that form at the interface between the fluids.

University of Florida



(Above) Unfolded ICECUBES hardware with the shaking system and four fluid-containing cells.

University of Florida

Viewing Vibrations in Space

The investigation launched on Northrop Grumman's 18th commercial resupply services mission. Controlling the system from the ground, the team performed 800 experimental runs over six months. Their goal was to see whether vibrating liquids in microgravity could unlock new ways to move heat, a crucial step toward keeping future space habitats safe and livable.

The team shook the containers at a set frequency. They started with a low amplitude and slowly built up to find the critical threshold where wave patterns would form. High-resolution video cameras captured the movement of the liquids.

"If we didn't have the wave patterns yet, we would increase the amplitude, and we'd continue to do this iteratively until we saw dramatic waveforms," Livesay said. "We'd do it for each of the test cells and then go back through and compare what we saw to our theoretical predictions."

It was a little complicated, though, because in space, the two fluids didn't stay in place with one interface between them like the team thought. Instead, one liquid encapsulated the other.

"That's part of the fun of working in space," Livesay said. "Sometimes it's a little unpredictable."

Despite the complication, the team was able to isolate the effects of surface tension, gleaning valuable insights. They also made an unexpected and exciting discovery. On the ground, when liquids are vibrated vigorously enough, the interface breaks, and one fluid disperses into the other. But in space, that did not happen.

"When we saw that the interface didn't break in space, it had a big implication," Narayanan said. "If it's not going to break, it means we could use Faraday waves in space for a number of things."

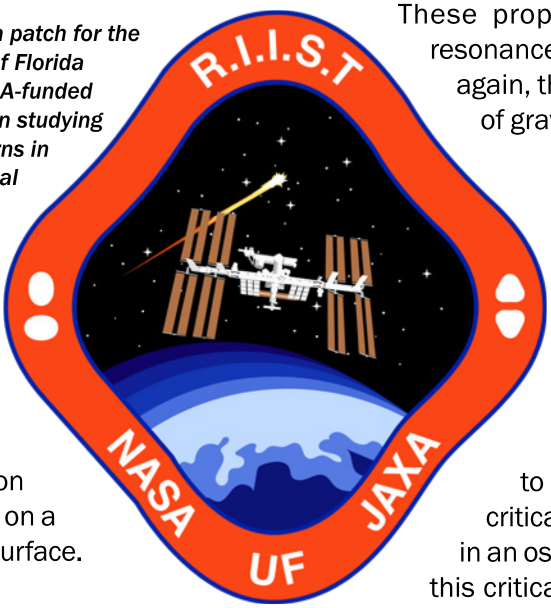
The next step is to test how well the fluid flow moves heat in microgravity, which the team will do in an upcoming investigation sponsored by the ISS National Lab.

"We have a lot of flow, and flow does something interesting—it's able to carry heat," Narayanan said. "Our hypothesis is that it's going to improve heat transfer enormously, which will ultimately be helpful for thermal management in space."

Applying Resonance to Additive Manufacturing

Building on their successful research, Narayanan and his team had another idea. They began work on a new ISS investigation, this time harnessing resonance to improve 3D printing with metals, particularly in remote locations like space.

"If you're going to make something in space, you better make it right the first time," Narayanan said. "It takes a lot of energy to make things, and power comes at a premium."



The mission patch for the University of Florida team's NASA-funded investigation studying wave patterns in molten metal spheres.
University of Florida

Additive manufacturing has valuable applications in remote locations on Earth, too. For example, someone could create a surgical implant for a wounded soldier while on the battlefield or make a specific tool on a submarine when there is no time to resurface.

"Many of these environments will have manufacturing facilities, where they're not just 3D printing plastic but 3D printing metals," Narayanan said. "You can't make mistakes because time is of the essence."

One method of 3D printing with metal uses a wire that comes out of a feeder. A heat source melts the wire to form a puddle of metal on a platform. As the platform moves back and forth, the liquid metal smears, forming a layer that solidifies as it cools. Layer by layer, a new tool or part is created.

However, there's a catch: ripples can form in the liquid metal. The platform must move at a specific speed, or it won't create a proper layer, Corbin explained.

"It will either be beaded up or wavy, and those imperfections will then be propagated throughout your system, so you'll have misprinted tools or just completely failed prints," he said. "You need to know surface tension and viscosity and other properties so you can get the correct speed and print your parts correctly."

These properties can be determined using resonance, but it isn't easy to do on Earth. Once again, the problem is the overpowering force of gravity.

Melting Metals in Microgravity

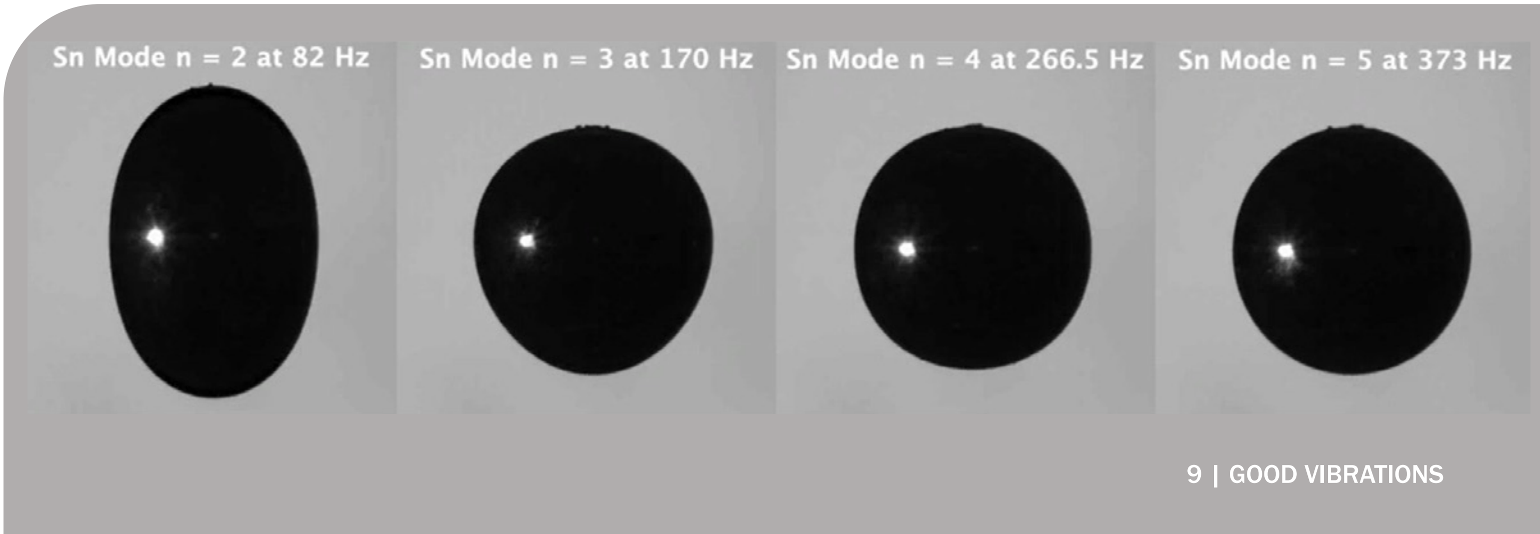
With a special furnace at NASA's Marshall Spaceflight Center, Narayanan and his team can use electrostatic force to levitate a liquid metal sphere. By applying an alternating current, they can move the sphere up and down, causing it to vibrate. When the sphere reaches a critical frequency, it begins to change shape in an oscillating pattern. Using a formula and this critical frequency, the team can calculate the surface tension of the liquid metal.

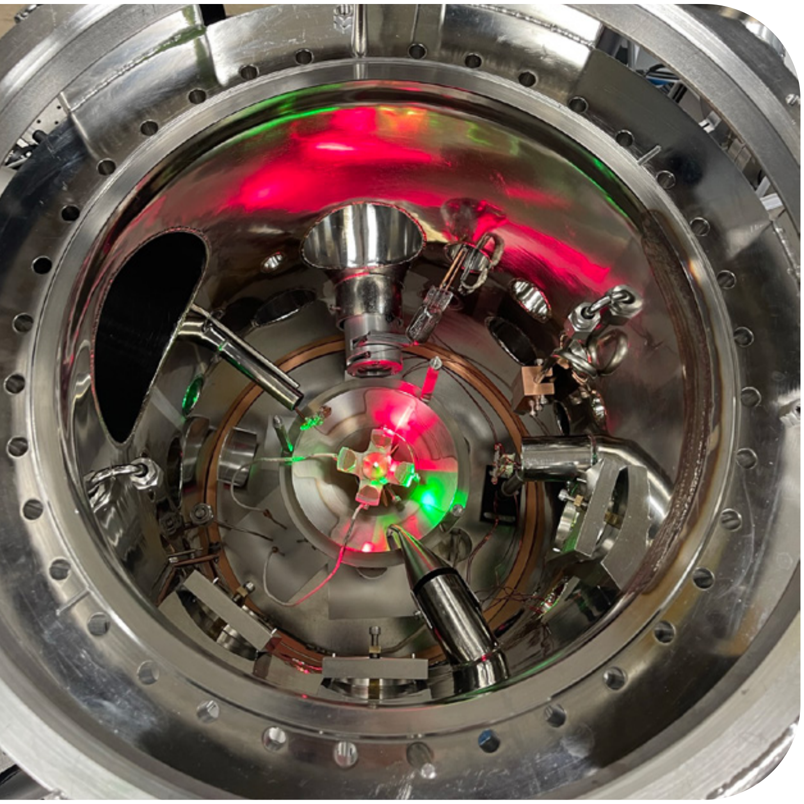
But metals are dense, and it takes a significant electrical force to keep even tiny metal spheres levitated. Also, gravity is pulling down, which can cause the spheres to sag and form more of a pear shape. To solve these challenges, the team again turned to space.

"In microgravity, because the metal sphere is already kind of free-floating, you barely have to hold it in place," Livesay said. "So, it makes it much easier to do."

In a NASA-funded project, the team collaborated with the Japanese Space Agency to use its electrostatic levitation

Levitated spheres of molten tin are shaken to observe Faraday wave patterns on the ground.
University of Florida and NASA MSFC





(Above) The ground-based levitator the team used to conduct molten metal experiments.

NASA MSFC

University of Florida team members Jason Livesay (back, far left), Ranga Narayanan (back, far right) and Thomas Corbin (front, center) with JAXA colleagues after completing their NASA-sponsored molten metals investigation.

JAXA

furnace in the Kibo module of the ISS. They levitated and vibrated six liquid metals, using high-speed video cameras to capture the motion of the two-millimeter-sized spheres.

The results were excellent, Narayanan said. The team developed a new method to measure the surface tension of liquid metals in space and could use a similar technique to determine viscosity. Based on these findings, the team filed two patents and submitted a paper to the journal *npj Microgravity*. They hope to use their new method to build a database of liquid metal properties for use in additive manufacturing.

“We’re looking at how we can provide accurate values of the surface tension and other properties so companies 3D printing with metals are not just predicting how the metal will behave, but they can actually know how it will behave,” Livesay said.

The Fundamentals of Fluid Flow

Whether you’re vibrating a container of liquid or a levitated metal sphere, Faraday instability gives rise to patterns, and these patterns can be put to good use, Narayanan said. It all comes down to understanding the fundamental science.

“We can now say we understand the science of this fluid motion,” he said. “We know we can use the flow to enhance heat transfer for thermal management in space and want to come up with a device based on this. We also know we can use it to find the correct viscosity and surface tension of metals for 3D printing, so we don’t have to print things again and again.”

Findings from the team’s ISS research will inform the development of critical technology for future missions on the Moon, Mars, and beyond. Every technological device we take for granted today has come from fundamental science, Narayanan explained.

“If you think the next generation of technology will come from the current one, it won’t—advances will only be incremental,” he said. “If you want to make the next leap, you need the fundamental science, and that’s what we’re hoping to show.”

SAVE THE DATE

ISS R&D Technical Sessions at ASCEND

May 19-21
Washington, D.C.

The International Space Station (ISS) National Laboratory will have dedicated technical sessions at ASCEND focused on space-based research. These sessions will spotlight the cutting-edge research and technology development enabled by the ISS and the unique environment of low Earth orbit.

Registration opens January 2026

Whether you're a researcher, engineer, industry leader, or space enthusiast, join us for these dynamic sessions that explore the frontier of science in space.

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Visit ISSNationalLab.org in the coming weeks for details on how to submit an abstract.

Reshaping Clean-Energy Design With Space Bubbles

Light-Activated Bubbles in Microgravity Reveal New Ways to Move Fluids

By Stephenie Livingston, *Staff Writer*

A bubble hovers inside a transparent cuvette as a beam of light strikes the fluid.
Yangying Zhu

By Earth's standards, the bubble wasn't supposed to move. But in a tube on the International Space Station (ISS), aimless and weightless, it suddenly slid sideways, chasing the spotlight.

"It almost dances in and out of the light," said Javier Read de Alaniz, an organic chemist at the University of California, Santa Barbara (UCSB). "So, as it shifts out of the light, it gets into a dark region, and it slows down. And then as soon as a tip touches light, it immediately moves toward that source."

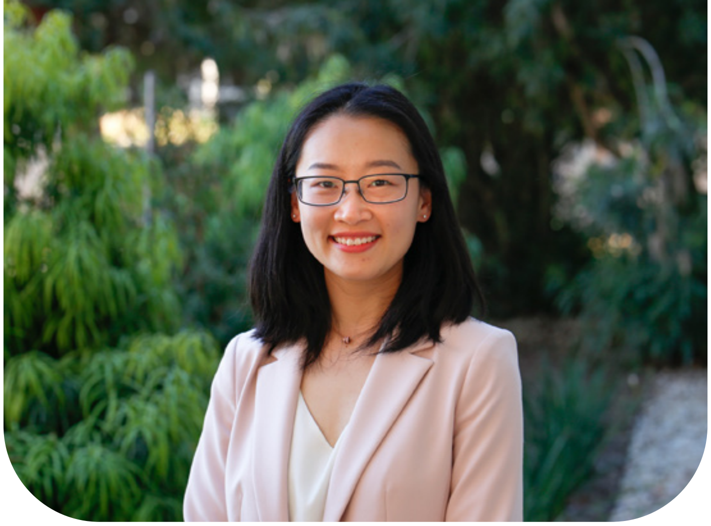
For the scientists who set out to move bubbles in microgravity with nothing more than light, it was years of preparation condensed into a simple, elegant moment.

Controlling fluids in microgravity has long confounded scientists and engineers. Without gravity, bubbles don't rise and escape; they cling to hot surfaces, forming an insulating layer that blocks heat. Droplets stick instead of sliding away, stalling the transfer of heat and fluids. Spacecraft cope with these quirks of microgravity by using workarounds that keep systems alive but add weight and complexity. What they can't do is take advantage of efficient processes that make power plants, air conditioners, and even laptops work on Earth.

This ISS National Laboratory®–sponsored experiment, which was funded by the U.S. National Science Foundation (NSF), found a new way forward. Yangying Zhu and her team became the first to use lab-engineered molecules and light to drive fluid motion in microgravity—a breakthrough they unveiled at the 2024 APS Division of Fluid Dynamics meeting and described in a 2025 *arXiv* preprint. Zhu, a mechanical engineering professor at UCSB, says the approach shows how light can precisely steer fluids in space.

"We hope that the knowledge we learn from this ISS experiment will contribute to enhancing boiling heat transfer, both on Earth and in microgravity, enabling more efficient power generation," she says. The same light-driven control could also inform cleaner energy design on Earth by laying the groundwork needed to move heat and fluids without pumps, cut energy losses in cooling systems, and build reactors that manage themselves.

This newfound fluid control could make spacecraft cooling systems lighter and more efficient, and the same principle may eventually transform technologies on Earth from data-center cooling to smart coatings that clean themselves at the flick of a light, says Read de Alaniz.



Yangying Zhu, principle investigator and a mechanical engineering professor at University of California, Santa Barbara.

Engineering Bubbles

Apollo astronauts noted with some surprise that drops of water clung to cabin walls instead of falling. In the 1970s, Skylab hosted some of NASA's first deliberate fluid physics experiments, where engineers tested how liquids wicked through narrow channels without gravity's pull. Shuttle-era Spacelab missions expanded the work, building chambers to watch bubbles and droplets form, merge, and drift. By the 1990s, U.S. Microgravity Lab flights onboard the shuttle had revealed how surface tension alone could drive flows invisible on Earth, a phenomenon known as thermocapillary flow, or the Marangoni effect.

The ISS picked it up from there: Europe's RUBI project studied boiling, NASA's ZBOT tracked boiling in propellant tanks, and even Delta Faucet flew a droplet experiment through the ISS National Lab in search of better showers. In partnership with NSF, the ISS National Lab has sponsored several fluid dynamics experiments, providing researchers with the resources to test whether fluid behavior in space could be steered. In one such experiment, for example, a research team from Auburn University published results detailing how saw tooth-structured surfaces could be used to force the movement of bubbles in heat exchangers in microgravity.

For Zhu and co-principal investigator Paolo Luzzato-Fegiz, also a mechanical engineer at UCSB, that possibility began in a NASA workshop in 2019. They listened as engineers described how boiling and condensation faltered in microgravity.

"In space, the bubbles are stuck on the surface. And they just accumulate, growing to larger, bigger-size bubbles," Zhu said. For someone who studies how to move heat efficiently, the image was striking.

Traditional fixes were costly, fragile, and power-hungry, relying on etched surfaces or high-voltage electricity. Zhu sought a different solution.

"We like the idea of a system that can be actively tuned and requires no surface fabrication," she said. "So, then we thought about using light."

To coax bubbles, Read de Alaniz slipped photosurfactants into the liquid, molecules akin to the ones that let shampoo foam by easing tension between water and air. Think of a bubble as a balloon with molecules clinging to its skin. Shine light on one side, and those molecules loosen their grip.

When light of a certain wavelength hits the molecule, its structure shifts, changing from water-repelling to water-attracting and altering its shape, he explained. "And then when you take the light away, then it will revert back, in this case almost instantaneously, to its original form."

Five fluid-filled cuvettes prepared for launch to the ISS as part of the investigation.
Yangying Zhu

On Earth, buoyancy seizes every bubble and lifts it before light can touch it. In space, that natural lift disappears. With nothing else moving the bubbles around, the tiny tug from light stands out. The team's investigation was, at heart, a twist on the Marangoni effect, the same surface-tension phenomenon shuttle crews once probed with temperature differences in drifting droplets. Here, though, Zhu and her colleagues showed it could be harnessed—the difference is that the surface-tension gradient is generated by the photosurfactants that respond to light and steer fluids in space.

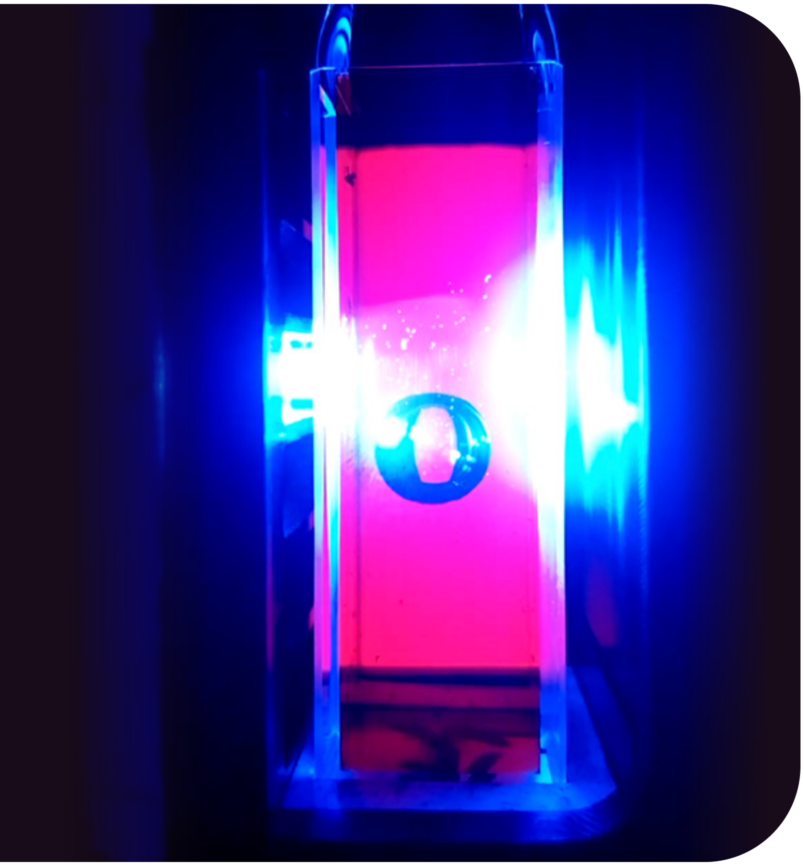
Groundwork for a Cleaner, Brighter Future

The hardware itself was simple: a CubeLab packed with fluids and a row of blue LEDs. "The tiny LEDs are very cheap, very low power," Zhu said, as if the investigation rested on nothing more glamorous than dollar-store bulbs.

But when the CubeLab reached Space Tango's facility in Kentucky for final integration, it refused to cooperate. Two of the team members and one of Read de Alaniz's graduate students bought last-minute tickets, flew out, and spent frantic days coaxing it back to life so it could make the launch window.

The team's investigation launched to the ISS on Northrop Grumman's 18th commercial resupply services mission for NASA.

Northrop Grumman



A bubble hovers inside a transparent cuvette as a beam of light strikes the fluid.

Yangying Zhu

Zhu never saw that launch in person. She was 35 weeks pregnant and couldn't travel. The experiment and the birth of her child are twinned in memory, she says.

After the investigation launched in November 2022, the team hit a roadblock nearly as soon as it got to the station. A heater inside burned out, spoiling a planned boiling test. Then, astronauts sent a video clip from another test using light, one that changed the mood entirely. When the video was replayed, the bubbles moved, gliding toward the light.

"Being able to watch it in real time, I think, was probably the most remarkable thing," Read de Alaniz said.

Tengfei Luo, a mechanical engineering professor at the University of Notre Dame who has also studied bubble dynamics on the ISS, called Zhu's work a fundamental study that does something extraordinary by cleanly isolating the physics of bubble motion from the distorting effects of buoyancy and convection.

"The team's methodology might help detach the bubble from the surface or guide substances from one place to another for chemical reactions or biosensing," he said, applications that could eventually aid heat transfer or robotic microfluidics experiments.

In the next iteration, Luo suggests testing different photosensitive molecules or light wavelengths, exploring how liquid viscosity shapes the effect, or even combining light-driven motion with surface interactions. Each variation, he says, would reveal another layer of how bubbles behave in space.

"The good thing about the ISS National Lab is that it not only funds specific applications, but also fundamental work like this project," Luo added. "The impact will be further amplified by the community, which can leverage the fundamental knowledge for diverse applications."

Seeing was believing for Read de Alaniz. "Seeing the droplet in the center of a cuvette with no gravity and then controlling it from thousands of miles away, you know, I think really speaks to what the potential could be," he said.

Luzzatto-Fegiz has used the video to develop theoretical models of fluid flow driven by photosurfactants. "The absence of gravity makes it possible to rigorously test our models," he says, "which then can be applied to other, general flows."

For Zhu, it also serves as inspiration. "I have undergraduate students basically saying that they want to do space-related research in the future after they see this experiment," she says.

The same light-responsive molecules that nudged bubbles on the ISS could one day inform new ways of making surfaces behave differently on demand. Read de Alaniz pointed to "smart" coatings that reset with a flash of light, creating surfaces that could shed buildup or toggle from sticky to slippery on demand. In industry, that could mean reactors that clean themselves, membranes that don't clog, or energy systems that restore with light—technologies that make energy production and heat management cleaner by design.

Luo agreed that such control could eventually be possible, though he emphasized that the study's strength lies in understanding the fundamentals of how light drives motion in weightlessness, which is knowledge others can build on.

As Zhu put it: "If you understand a process fundamentally, that opens up doors to not just one thing, but maybe ten other things."

It's how, after decades of watching bubbles misbehave in space, someone finally got one to listen.

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FORGING THE PATH

By Ray Lugo | CASIS CEO

Ray Lugo serves as chief executive officer of CASIS, manager of the ISS National Lab. Within this role, he is responsible for implementing strategic objectives that enable space-based research that brings value to our nation and builds a robust and sustainable market.

We're on the Brink of Losing Space Leadership—Here's How We Can Reclaim It

After more than 50 years in the space industry, I've learned this: America's leadership in space doesn't come guaranteed—it's earned. Today, that leadership is at risk. When I was young, I witnessed America's greatest accomplishment in space, the Apollo Moon landing. Then, as an adult, I participated in the continuation of U.S. dominance of the high frontier with the International Space Station (ISS). Never in my lifetime did I consider that we, as a nation, would cede our preeminence in space to a foreign adversary. Yet today, I feel that is a very real possibility.

Since the start of this fiscal year, I've grown increasingly uneasy about our position as the world's leader in the peaceful exploration of space. As someone who grew up watching our nation's most celebrated space achievements, I've always believed our dominance in space is essential to our national security—both economic and physical. But now, I fear we're on the verge of surrendering that dominance.

A significant threat looms: retiring the ISS in 2030 without an agreed-upon replacement. NASA has spent years planning for one or more commercial successors, but a change in administration and its proposed deep budget cuts for NASA have stalled progress. This threatens not only our microgravity research capabilities but also our 25 years of continuous human presence in space—just as we begin to unlock the economic potential of space-based R&D.

Over the past 12 years, the ISS National Lab has laid the foundation for a strong economy in low Earth orbit (LEO). Much like the telecommunications boom sparked by Telstar 1 in the 1960s, the LEO economy could become the next trillion-dollar industry within a decade. We're already seeing breakthroughs in materials science, pharmaceuticals, and biotechnology—advances that could transform life on Earth. But all of this is now at risk.

Many Americans may not fully grasp the stakes. In the 1950s, the Soviet Union's launch of Sputnik shocked the U.S. into action. That wake-up call led to the Moon landing and decades of innovation. Since then, we've led a coalition of nations in peaceful space exploration, reaping benefits like global satellite telecommunications and valuable scientific breakthroughs. But while we now partner with Russia on the ISS, China is emerging as the more significant strategic competitor in space.

Some may not realize the scale and ambition of China's space program. Their goals mirror the bold vision the U.S. had in the 1960s: to dominate LEO, establish a permanent presence on the Moon, and eventually explore and settle Mars. China's efforts are strategic, coordinated, and multifaceted—and we cannot assume their intentions align with ours.

In just over four years, China has completed the core of its space station, crewed by three astronauts who are also officers in the People's Liberation Army. Expansion plans are already underway. China is also aggressively pursuing a human mission to the Moon—and by some estimates, they may be ahead of the U.S. in this effort. A sustained lunar presence is the stepping stone to Mars. And while China may not have surpassed us yet, without deliberate planning and action, we risk falling behind.

We also risk losing our country's leadership and security that has taken 250 years to build. The good news? The solution is within our collective power—if we choose to act.

We've faced setbacks before. The Challenger disaster in 1986 exposed the risks of relying on a single launch system. We adapted, rebuilt a diversified space shuttle fleet, and helped launch the New Space economy. When the Space Shuttle Program was retired in 2011, we had to rely on Russia's Soyuz spacecraft to transport our astronauts to the ISS until SpaceX's Dragon restored U.S. crew transport in 2020. Now, we must rise to the challenge again.

In the 1960s, the U.S. led the world in R&D investment, spending twice as much as the rest of the world combined. Today, we spend less than half of what our allies invest collectively. The current budget proposal continues that downward trend.

Consider this: NASA receives less than 1 percent of the federal budget. Even when combined with the U.S. National Science Foundation and the National Institutes of Health, the total investment in science and technology is only about 2 percent. Yet these are investments that yield exponential returns.

Yes, the federal deficit is a serious issue. But cutting investment in innovation is not the solution. That approach risks contracting the economy, eliminating jobs, and drastically reducing future economic gains. A more constructive path is to invest in growth. That's how America has always moved forward—by building, creating, and expanding.

We've established a robust LEO economy. We've broken ground on a lunar economy. Our robotic missions to Mars position us to lead there as well. But we cannot lead with a short-sighted vision like the one reflected in the 2026 budget proposal.

Restoring NASA's budget to 2024 levels isn't just a smart investment—it's a strategic imperative. The future of American leadership in space depends on it.

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