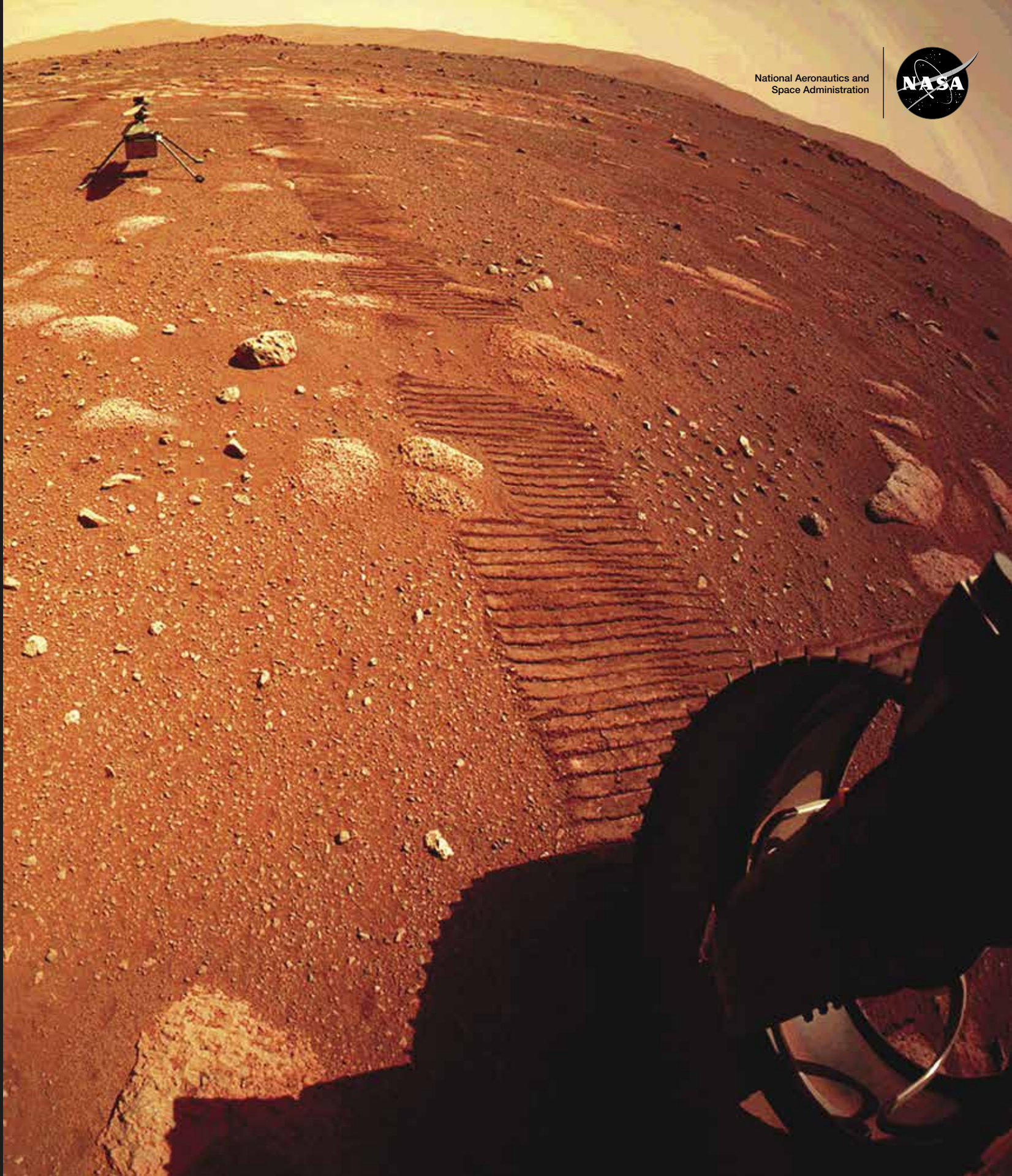
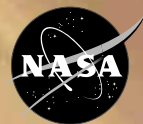


JET PROPULSION LABORATORY 2021

National Aeronautics and  
Space Administration





JPL  
2021  
ANNUAL  
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# INTRODUCTION

**ON APRIL 19, 2021**, the Ingenuity Mars Helicopter hovered for the first time over the surface of another planet, capturing the world's imagination. This autonomous, solar-powered flight depended on creative and meticulous design, advancing from a technology demonstration to a valuable scientific tool.

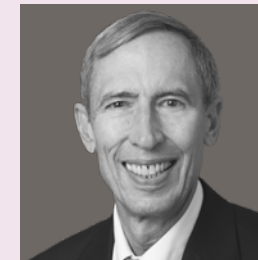
JPL engineers, scientists, and staff are deeply familiar with the challenge of navigating critical missions in the face of unpredictability. This was demonstrated most impressively last year against the backdrop of a resurgent Covid-19 pandemic and organizational transitions. The Lab's salutatory track record, which included the launch of innovative instruments to monitor weather systems and recordings of radio emissions from Ganymede, among many achievements, is a testament to the formidable talent and experience at JPL. Caltech is proud to partner with NASA to push the boundaries of scientific and technological achievement.

We are grateful to Dr. Michael Watkins, who directed JPL from 2016 to 2021, and General Larry James, who serves as interim director, for their skillful and inspiring leadership. At the same time, we look forward and extend a warm welcome to Dr. Laurie Leshin as we prepare to embark on JPL's next chapter. Under her guidance, we will build on an extraordinary legacy and explore uncharted realms. Integral to this future will be the recruitment and retention of a talented and diverse workforce that enriches the already vibrant JPL community. Together, we will position the Lab to illuminate new worlds and the mysteries of our own planet Earth.

Let us celebrate the accomplishments of 2021 as we commit ourselves to a year of accomplishment and significance ahead.



**THOMAS F. ROSENBAUM**  
President, Caltech



**LARRY JAMES**  
Interim Director, JPL

# DIRECTOR'S MESSAGE

**WHEN FUTURE GENERATIONS** look back on 2021, they will see an entire planet in the pall of pandemic, and a neighboring world marked with a speck of the uncontrollable human spirit.

That speck came from JPL. The Perseverance rover and Ingenuity helicopter landed safely on Mars on February 18, 2021, less than a year after the worldwide outbreak of Covid-19. Perseverance is the most advanced in a long line of Martian rovers from JPL, and Ingenuity, modestly described as a "technology demonstration," achieved the first powered, controlled flight on another planet — and many more after that initial leap into the Red Planet's thin atmosphere. Our little helicopter, which carried a tiny patch of fabric from the Wright Brothers' first plane, became a worldwide phenomenon.

Closer to home, but still a million miles from Earth, our Mid-Infrared Instrument on the James Webb Space Telescope is set to reveal the early universe with observations that for the first time will show us the earliest stars and galaxies.

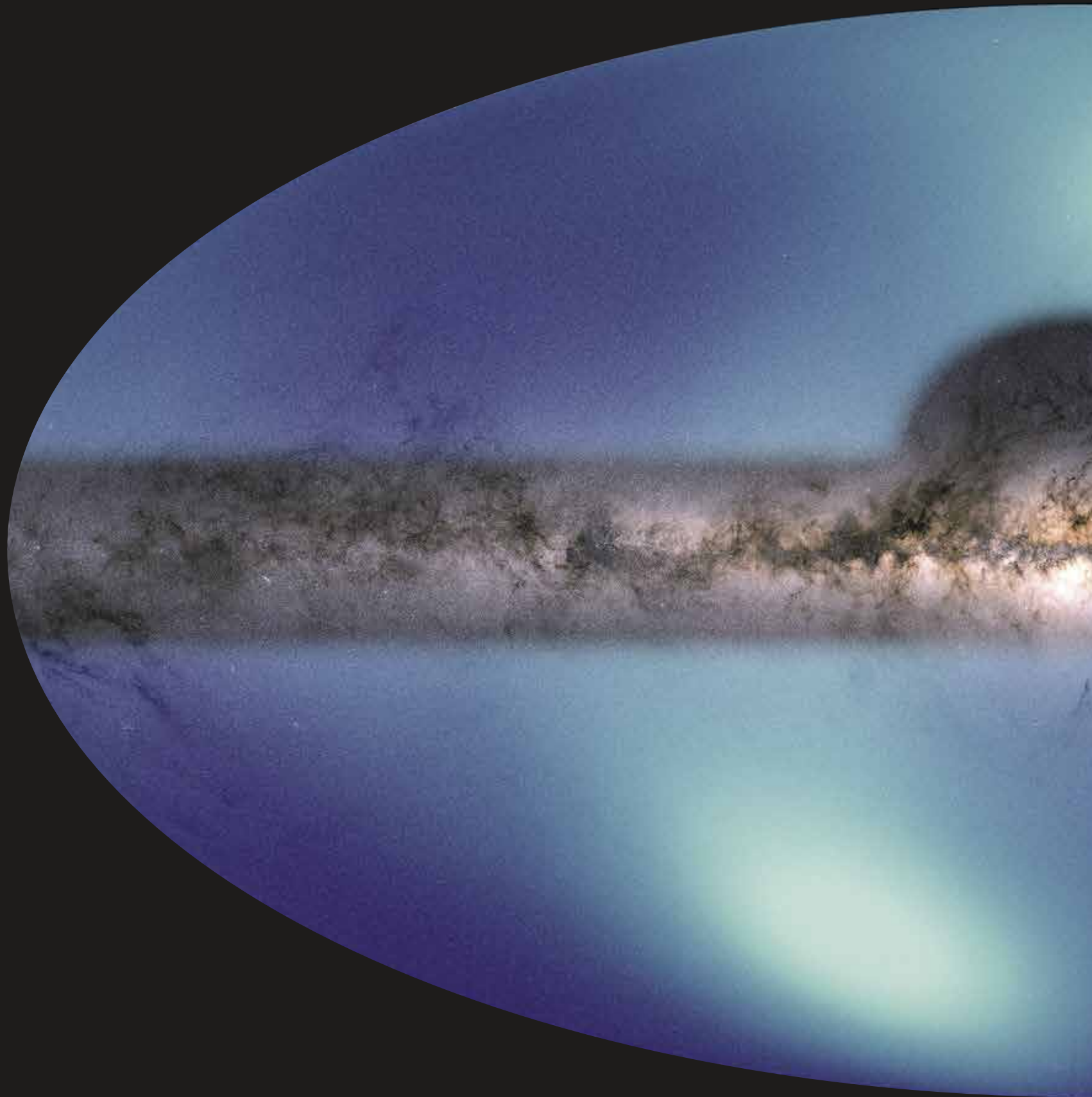
A few hundred miles above us, Sentinel-6 Michael Freilich is extending a long-running series of sea level measurements. Here on Lab, work continues on the Nancy Grace Roman Telescope Coronagraph Instrument, which will demonstrate new technologies to suppress starlight in order to study exoplanets. In the following pages you may also recognize the names of some of our many missions marching toward launch, such as Psyche, SWOT, Europa Clipper, NISAR, and the newest mission awarded to JPL in 2021, VERITAS.

Our Deep Space Network supported multiple deep space missions, from Mars 2020 to Lucy, and opened 2021 by placing in service a new 34-meter antenna dish and returning to service the overhauled 70-meter dish that connects Earth to Voyager 2 in interstellar space.

We also strengthened our ties to industry partners and federal funding agencies, including the Department of Homeland Security, the National Oceanic and Atmospheric Administration, the Air Force and the Defense Advanced Research Projects Agency. Our innovative partnership with the philanthropic community and industry has led to the Carbon Mapper project, using our space instruments technology to pinpoint global methane emissions, and the National Institutes of Health is using JPL big data science to support cancer research.

None of these accomplishments would be possible without the incredible dedication, creativity and diversity of our JPL community. Last year I was proud to accept, on behalf of the Lab, the International Astronautical Federation 3G Diversity Award. Also in 2021, JPL appointed our first Diversity, Equity and Inclusion manager.

We have an awesome team that always pulls together to focus on the mission and get the job done, with or without a global pandemic. I could not be prouder of our community, and I know our incoming director Dr. Laurie Leshin will find the Lab a place of warmth, inspiration and daring. We will continue to Dare Mighty Things, together!



# UNI VER SE

**FAINT PLANETS AND STARS AWAIT** discovery from JPL-designed instruments that will also search for the spectral signatures of the oldest galaxies in the universe, and block the glare of starlight to observe the terrestrial bodies that orbit distant suns.

## REFINED VIEWS OF "THE OLD, THE COLD AND THE DIRTY"

**THE JPL-MANAGED SPITZER SPACE TELESCOPE** was once described as observing "the old, the cold and the dirty" out in space. JPL extends this proudly self-deprecating tradition with the Mid-Infrared Instrument (MIRI) on the James Webb Space Telescope.

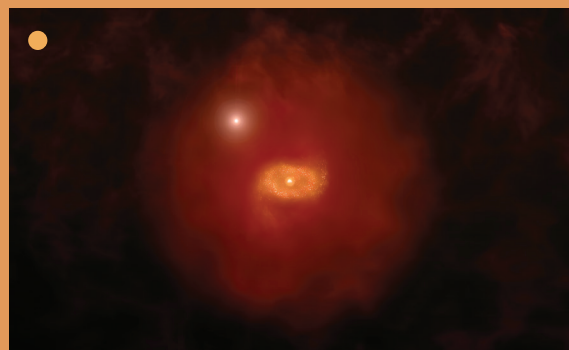
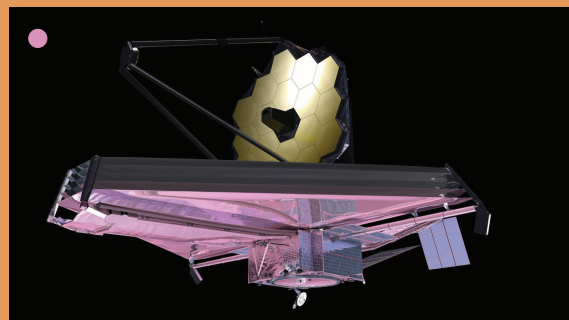
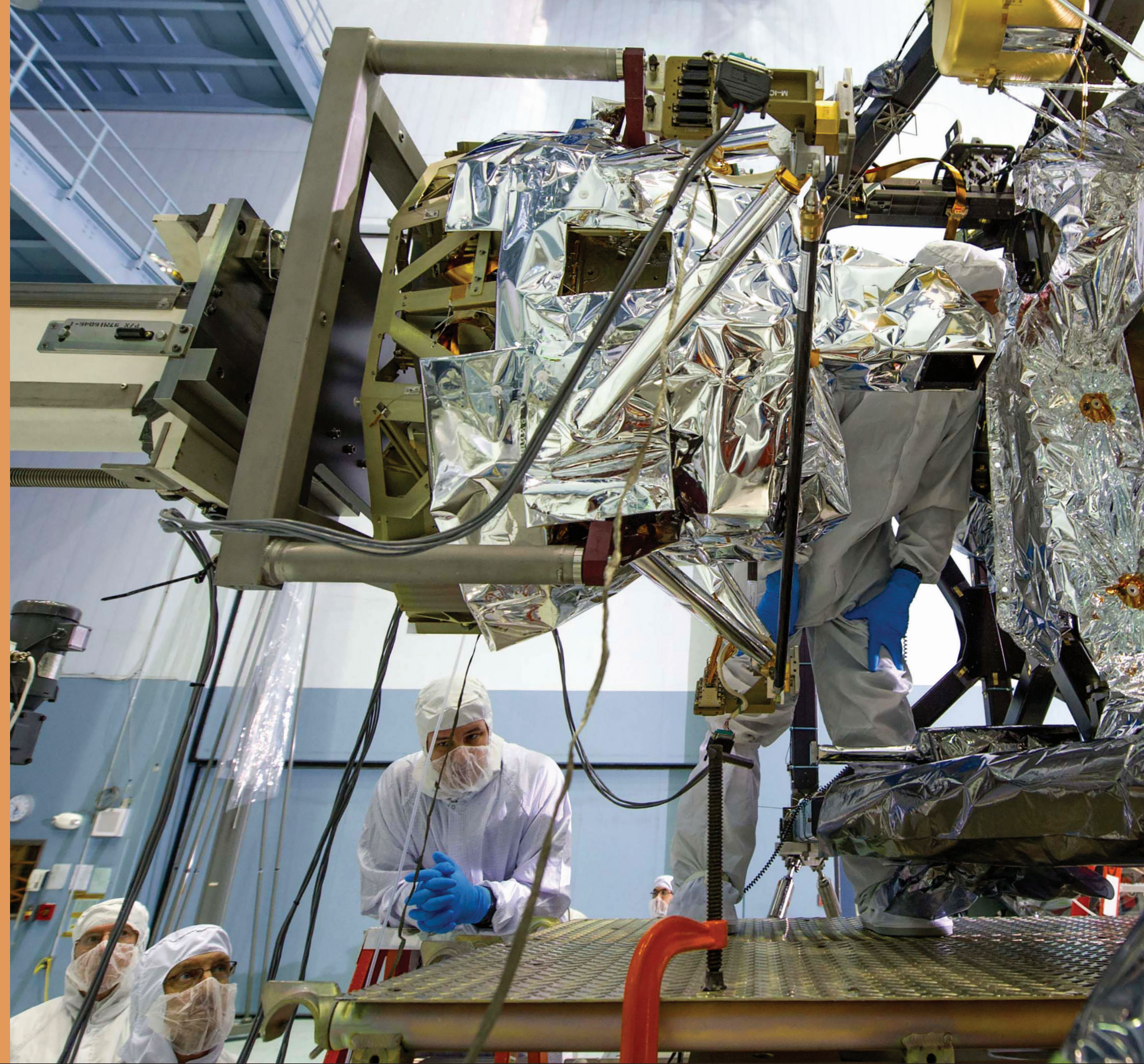
The oldest and most distant objects in the expanding universe are receding the most rapidly from Earth. As the wail of its horn drops in pitch after a train passes a crossing, what was visible light from the oldest objects in the universe has stretched into the infrared spectrum as it reaches Earth. Much of that light is in the poorly explored mid-infrared. MIRI will help fill the gap and identify some of the first light-emitting objects after the Big Bang, helping astronomers understand how galaxies were formed.

MIRI also will analyze the atmospheres of room temperature brown dwarfs to help explain how these "failed stars" formed, and the atmospheres of cool planets to reveal the unimagined diversity of planetary systems. And the instrument will peer into the nurseries of the universe, dense clouds of gas and dust that harbor the youngest stars and planets.

While Webb's three other scientific instruments operate in near-infrared wavelengths and can function without issues at a toasty 40 kelvin, MIRI needs to be cooled to 6 kelvin to avoid detecting its own heat. Using technology developed under the JPL-led Advanced Cryocooler Technology Development Program in the early 2000s, Northrop Grumman Space Systems produced MIRI's unique space refrigerator. Integrated into Webb by JPL, the cryocooler presented extraordinary challenges during installation and testing because its components are distributed throughout the observatory.

MIRI was built with partners from 24 European astronomical institutes. JPL provided the detector subsystem with its control electronics and software, while the European partners provided the optics and instrument structure and assembled the instrument.

The observatory rose to space atop the European Space Agency's Ariane 5 rocket on Christmas Day, 2021. MIRI is expected to start exploring the undiscovered early universe in the summer of 2022.



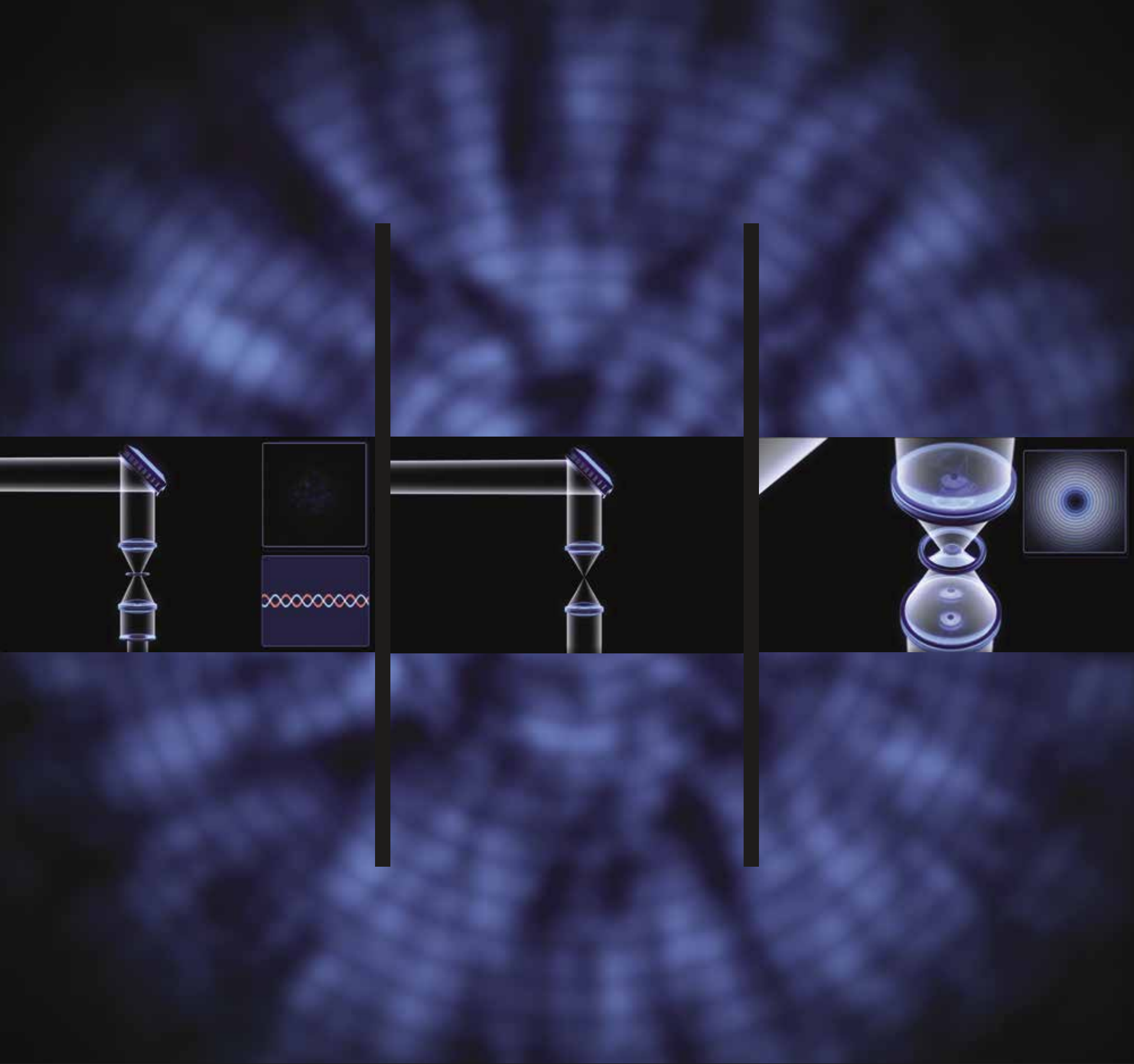
MIRI will play a key role in the Webb telescope, studying stars and galaxies in infrared light.

Artist's impression of a high redshift Milky Way-like galaxy  
Credit: Alexandra Angelich (NRAO/AUI/NSF)

Installation of MIRI into the instrument module

UNIVERSE

7



## I CAN SEE CLEARLY NOW THE GLARE IS GONE

**ARE THERE OTHER PLANETS** like Earth in the galaxy? To answer that question, astronomers will need to directly image candidate Earth twins. The problem is that the host stars for these Earth-like planets outshine them by 10 billion to 1, and the planets are lost in the glare. Astronomers will need the best pair of “starglasses” ever built. JPL is playing a leading role in developing and maturing multiple key technologies for these spectacular spectacles in the Roman Coronagraph Instrument. A system of masks, detectors, and even self-flexing mirrors, the instrument is a JPL-designed technology demonstration.

The Nancy Grace Roman Space Telescope, planned to launch no later than 2027, will use JPL’s instrument to dim starlight by a factor of about 1 billion, allowing astronomers to image true Jupiter twins for the first time.

As light that has traveled tens of light-years from an exoplanet enters the telescope, the instrument’s thousands of actuators will move like pistons, changing the shape of the self-flexing mirrors to fine-tune the telescope’s optics. These mirrors will work in tandem with microfabricated “coronagraph masks” to suppress the starlight. The result: the first views in human history of planets revolving distant suns.

The Roman Coronagraph Instrument will prove many of these technologies in space for the first time, paving the technological path for a future NASA mission that aims to image a planet like our own.



# EARTH'S BOUNCER

**THE SPACE BETWEEN PLANETS** is vast, but it's not empty.

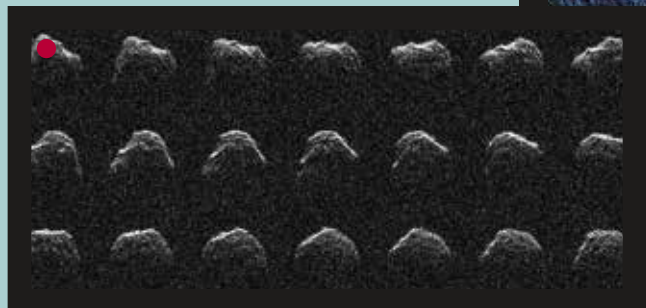
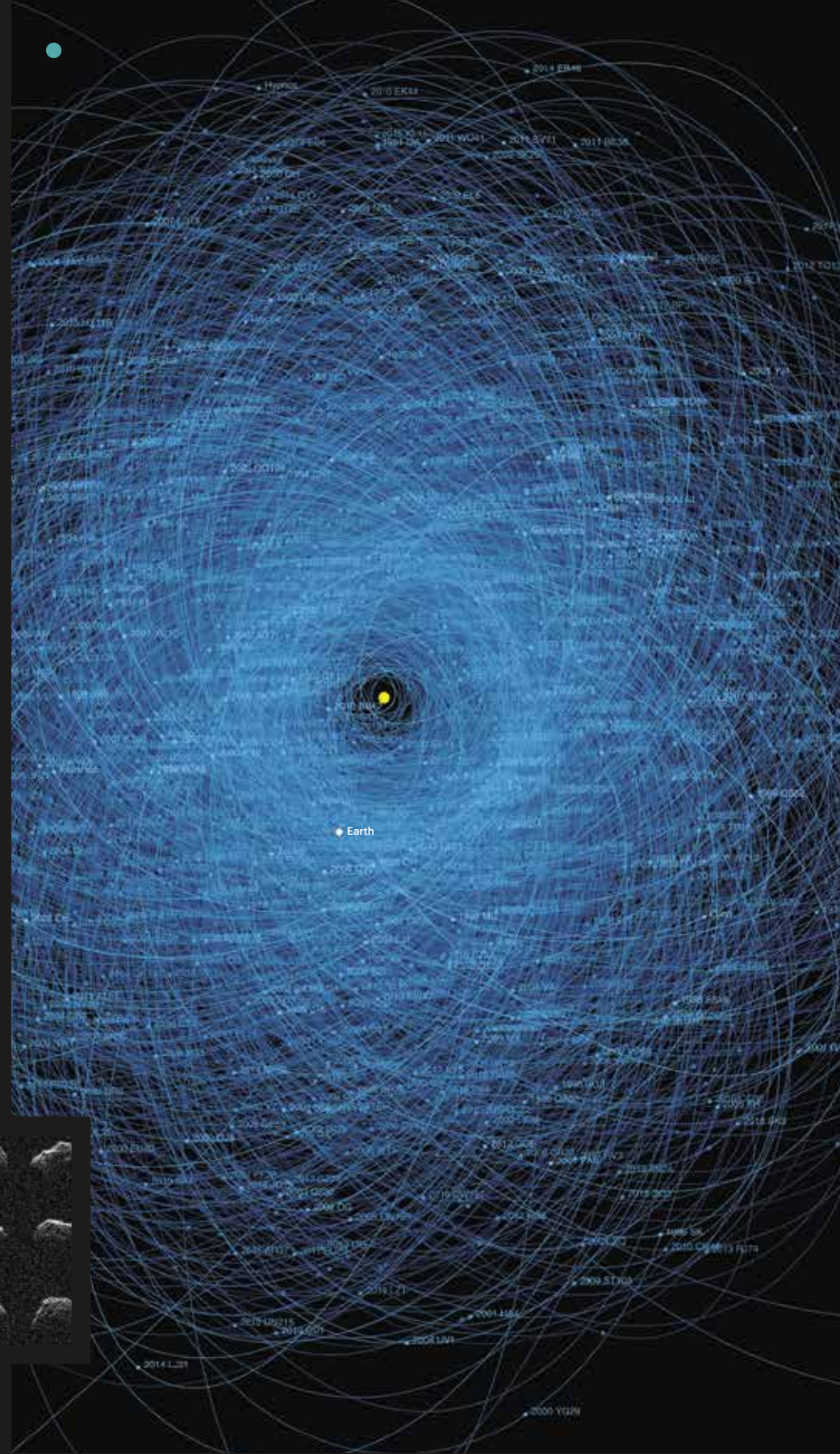
Earth is bombarded by small meteors — small fragments of asteroids or comets — every day, most of which burn up completely in our atmosphere without crashing to the surface as meteorites. Scientists currently know of about 25,000 asteroids, classified as Near-Earth Objects (NEOs), any one of which could wipe out an area the size of Southern California or more if it hit the Earth. If one is indeed heading for us, we might be able to deflect it (see the DART mission that NASA launched in 2021). But we have to find it first.

Right now, ground-based telescopes are the primary means of detecting NEOs, but they can't search during bad weather or during the daytime, and most importantly, they can't see through the Earth's atmosphere at the mid-infrared wavelengths where the asteroids radiate heat.

The solution?

Park a space telescope between Earth and the Sun and scan regions of space we can't see well from Earth, at wavelengths that don't get through the atmosphere.

This is the impetus behind NEO Surveyor, NASA's Near-Earth Object Surveillance Mission slated for an early 2026 launch. NEO Surveyor will look ahead of and behind Earth's orbital path, spotting perhaps 10 times as many asteroids as are known to date.

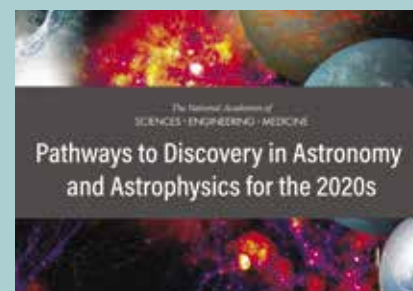


● Radar reveals the surface of Asteroid 2016 AJ193

● Orbits of 2,200 potentially hazardous objects  
Credit: Paul Chodas, CNEOS SSD



# THE STARS ALIGN FOR ASTRO2020 DECADAL



**WHAT ARE THE KEY** scientific challenges for astronomy and astrophysics in the next decade?

*Pathways to Discovery in Astronomy and Astrophysics for the 2020s*, the National Academies' latest decadal survey released in November of 2021, identified the most compelling science goals and presented an ambitious program to support the foundations of the profession, as well as the technologies and tools needed to carry out the science.

In many cases, JPL was already on it. Astro2020 validated the Lab's ongoing development of far-infrared detectors, as well as the mid-infrared capabilities now in place on the James Webb Space Telescope. Another Astro2020 priority — the observation of exoplanets, and especially Earth-like candidates — has been a focus of scientific investment at JPL for decades. That investment manifested most prominently in 2021 through substantial progress in manufacture of the Roman Coronagraph Instrument, with its innovative light-masking technology.

A close up of M16, also known as the Eagle Nebula



# PLANETARY NET ARRAY

AS ONE MISSION LANDED – and flew – on the Red Planet, the next began. Mars Sample Return will collect Perseverance’s samples of rock, soil and atmosphere, bringing scientifically-selected extraplanetary matter back to Earth in another first for humanity and NASA.





# YOUR MARS SAMPLE IS READY TO SHIP

**ON SEPTEMBER 1, 2021**, NASA's Perseverance rover unfurled its arm, placed a drill bit at the Martian surface, and drilled about 2 inches (6 centimeters) down to extract a rock core. The rover later sealed that core in a titanium sample collection tube. This historic event marked the first time a spacecraft packed up a rock sample from another planet that could be returned to Earth by future spacecraft.

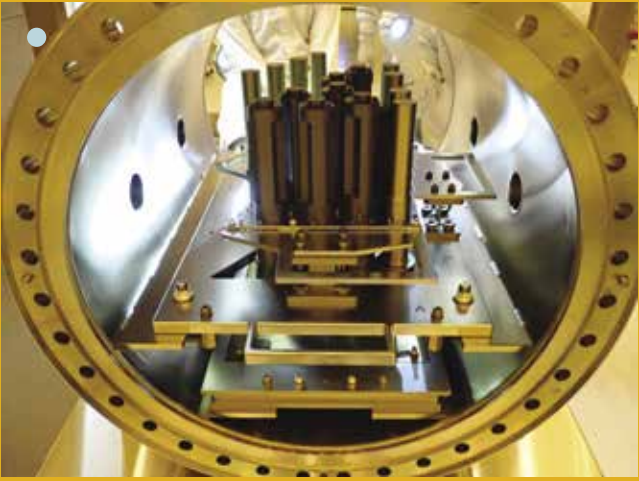
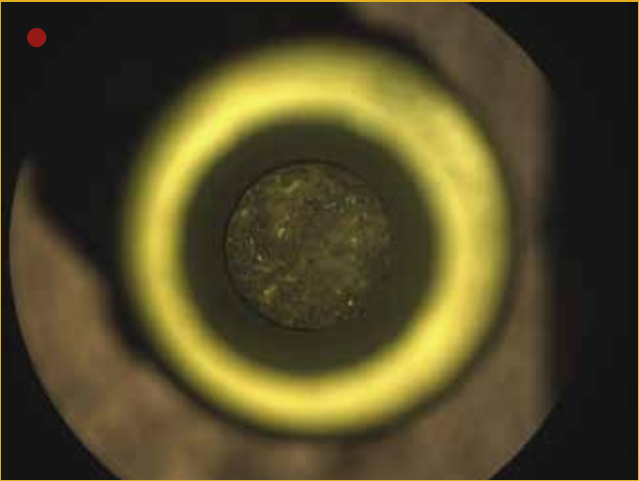
Mars Sample Return is a multi-mission campaign designed to retrieve the cores Perseverance will collect over the next several years. It is one of the most ambitious endeavors in spaceflight history, involving multiple spacecraft and launches.

The benefit of analyzing samples back on Earth is that scientists can use cutting-edge lab technologies to complete analyses much faster on whether life ever existed on Mars.

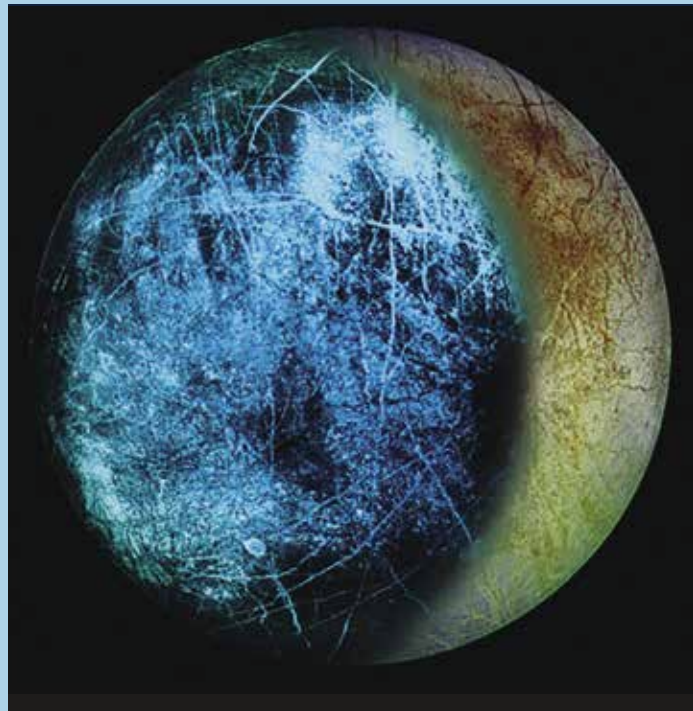
To safely return Martian samples to Earth, NASA is partnering with ESA and multiple U.S. government departments and agencies, including the U.S. Centers for Disease Control and Prevention and the U.S. Department of Homeland Security, in helping design systems to protect the Martian samples from contamination throughout their journey from Mars to Earth.

Success at Mars is also a critical pathfinder for potential sample-return missions to Europa or Enceladus, where future expeditions could collect and return fresh ocean plume samples to be analyzed for potential extraterrestrial life.

Perseverance made history above as well as below ground. The Ingenuity helicopter proved the feasibility of powered, controlled flight on other planets, and carried on its slender frame a tiny patch of fabric from the Wright Brothers' first airplane. Another technology demonstration showed that future explorers will be able to make oxygen from the Martian air. And on the gripping descent from space, terrain-relative navigation autonomously guided Perseverance to a safe landing site.



## EUROPA: DIFFERENT ENERGY HAS GOOD CHEMISTRY FOR LIFE



**OVER THE PAST FOUR BILLION YEARS**, Europa has been stretched and squeezed like taffy. For any potential life, that's a good thing.

The kneading of Europa is caused by gravity, and is known as tidal heating. Tugs from the giant parent planet, Jupiter, with help from fellow moons Io and Ganymede, heat up Europa's interior.

This heating energy has likely allowed a vast ocean beneath Europa's icy shell to remain liquid for the entire history of our solar system. That means the same forces that set the stage for the development of life on Earth — a steady heat source, liquid water and plenty of life-friendly chemistry — also could have existed on Europa.

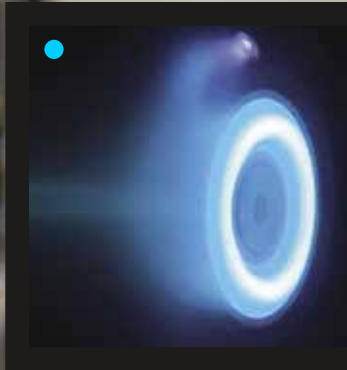
In the fall of 2021, NASA gave the green light to Europa Clipper's plans to begin assembly and testing in 2022 — another major milestone successfully completed on its way to a planned 2024 launch.

Europa Clipper will orbit around Jupiter and conduct multiple close flybys of its moon Europa to gather data on its atmosphere, surface, and interior.

Missions such as Europa Clipper contribute to the field of astrobiology, the interdisciplinary research on the variables and conditions of distant worlds that could harbor life as we know it. Understanding Europa's habitability will help scientists better understand how life developed on Earth and the potential for finding life beyond our planet.



This illustration of Europa shows how the icy surface may glow on its nightside, the side facing away from the Sun, potentially due to radiation from Jupiter's magnetic field.



## PSYCHE, SEP, AND SUMMER

**AS OF THE TIME OF PRINTING** this annual report, the fully assembled Psyche spacecraft was completing testing at JPL prior to being shipped to NASA's Kennedy Space Center in Florida, for a launch window that opens August 1, 2022.

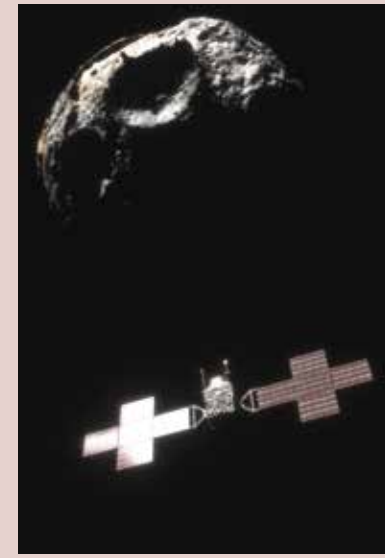
Psyche's target, an asteroid of the same name in the main asteroid belt between Mars and Jupiter, is made of a significant fraction of iron and nickel and could be the core of an early, rocky planet.

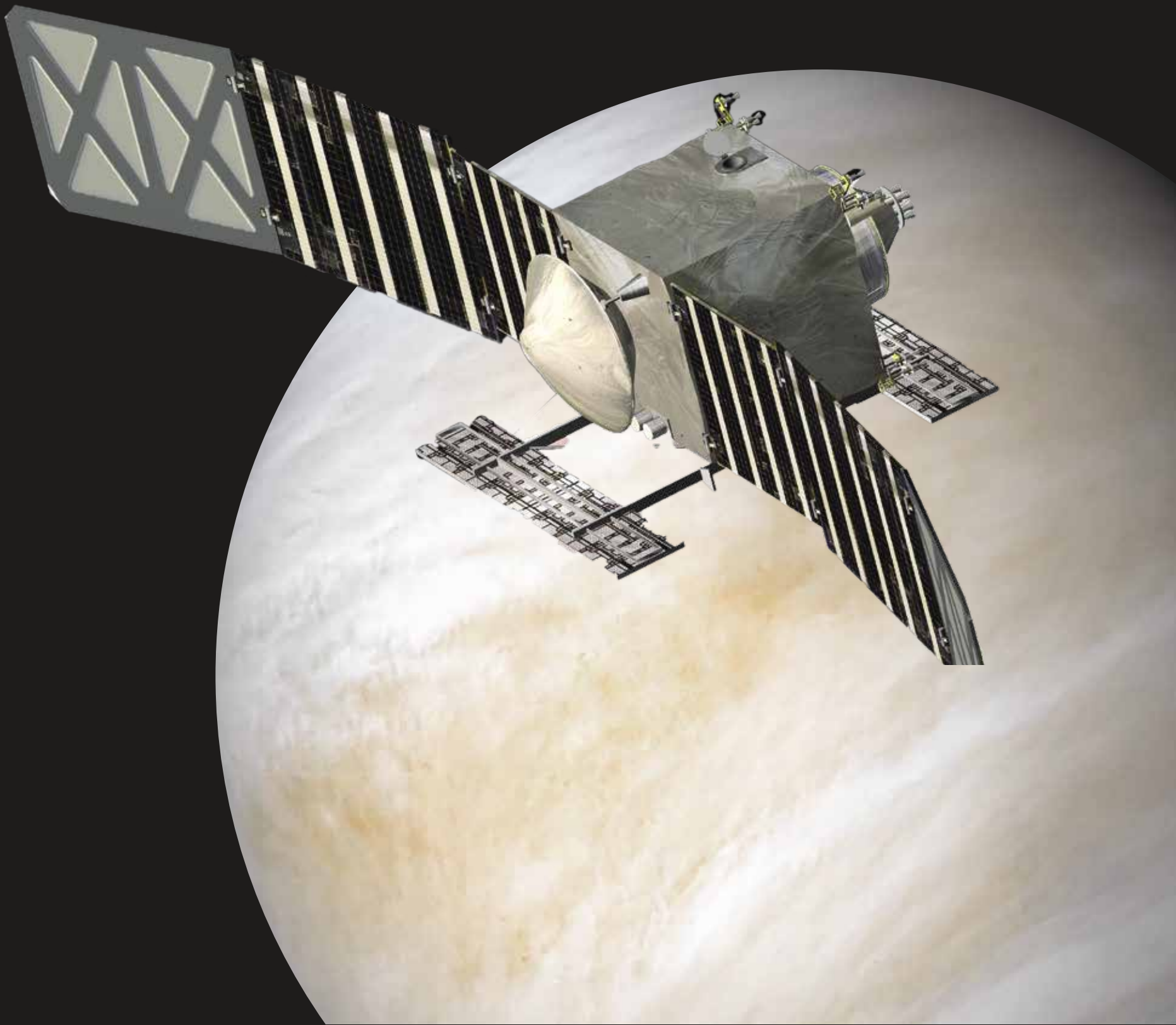
"Building this complex, precision piece of engineering during the year of Covid is absolutely a triumph of human determination and excellence," said Principal Investigator Lindy Elkins-Tanton.

When it comes time to power through deep space, solar electric propulsion (SEP) emitting a cool blue glow will guide Psyche on its three-year, 1.5 billion-mile cruise through deep space. The Psyche spacecraft will extend the use of Hall thrusters into deep space for the first time, propelling this mission to the main asteroid belt between the orbits of Mars and Jupiter.

Arriving at the asteroid in 2026, Psyche will spend 21 months orbiting the 140 mile-wide asteroid, mapping it and studying its properties. The information won't just help scientists understand this particular object: it will lend valuable insight into how Earth and other planets formed.

The mission also will test a sophisticated new laser communications technology, recently completed by JPL, called Deep Space Optical Communications (DSOC). This technology demonstration will use lasers to communicate, preparing NASA for data-intensive transmissions which could potentially include livestreamed videos for future missions.





Artist's concept showing the proposed VERITAS spacecraft



Artist's concept of an active volcano on Venus surrounded by a theorized subduction zone

## VENUS: RENAISSANCE PLANET



**ON JUNE 2, 2021**, NASA Administrator Bill Nelson went all in for Venus by selecting JPL's Venus Emissivity, Radio Science, InSAR, Topography and Spectroscopy (VERITAS) mission along with Goddard's DAVINCI+ mission. Later that month, ESA announced that its EnVision mission, complete with a JPL-provided synthetic aperture radar, would also take part in this new era of Venus exploration. Together, these missions form a comprehensive science program of the second planet in our solar system. For NASA, these are the first such investigations in nearly 40 years.

If Earth had a sibling, its name would be Venus. In many key ways, Earth and Venus are strikingly similar: nearly the same size, gravity, density, mass, and chemical makeup. At some stage, though, the characteristics of the geological activity of the two planets diverged. Earth's solid lid cracked into plates, colliding to create vast mountain ranges or pulling apart to create giant rifts or new crust. Earth's plate tectonics help to modulate our atmosphere, regulating the amount of carbon dioxide on our planet over long timescales.

Today, Venus has no discernable plate tectonics system, but may still have volcanic activity as its surface seems to have been resurfaced with lavas as recently as half a billion years ago. Its volcanoes were likely powered by thermal plumes rising through the mantle — created in a process that can be likened to a 'lava lamp' but on a gigantic scale.

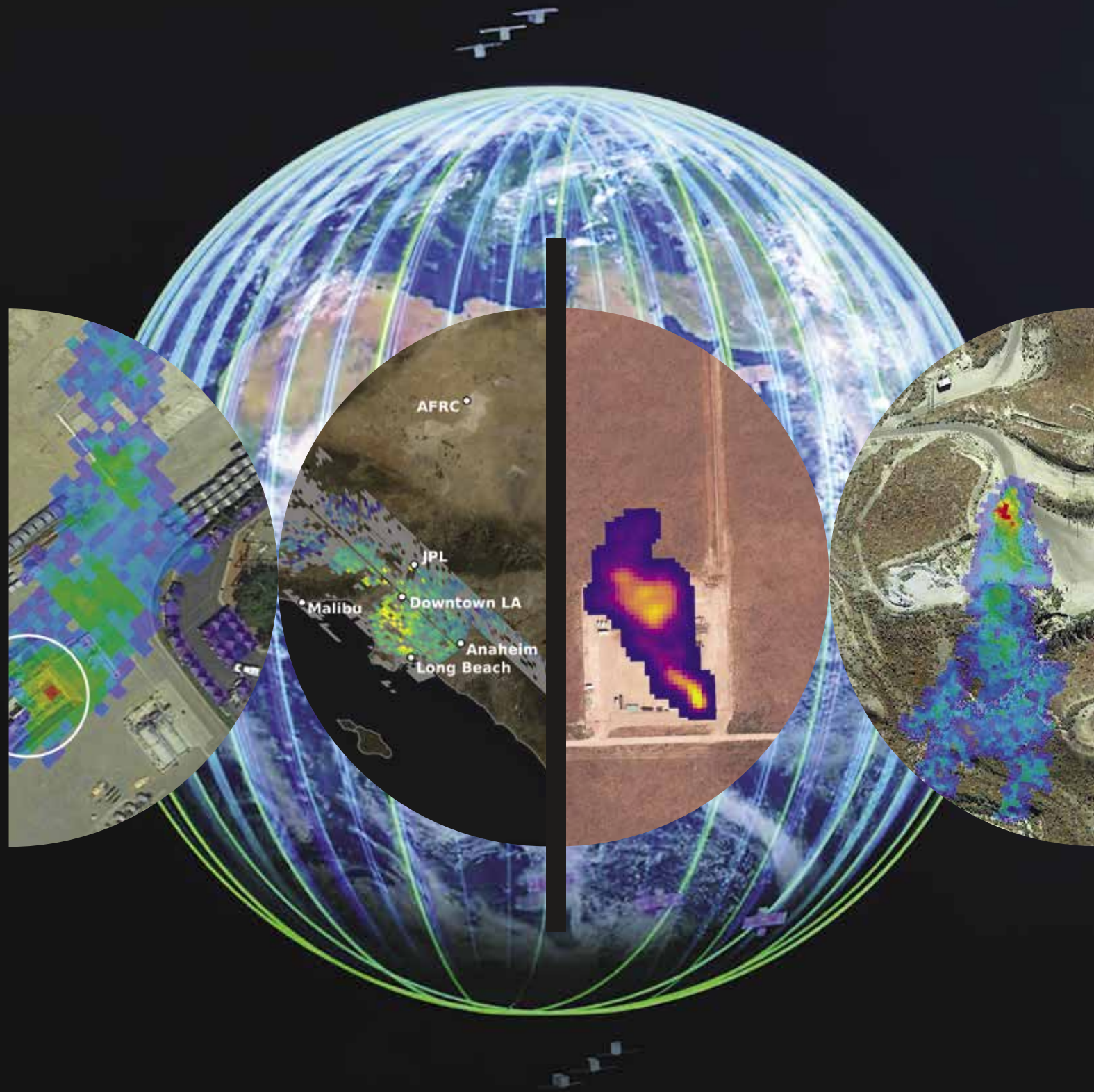
Understanding how the surface and interior of Venus evolved is valuable given the similarities between Earth and Venus. The mechanics that led Venus to heat up could help scientists here on Earth better understand our own changing climate — acting as a test case of what happens when a runaway greenhouse effect takes charge.

The mission's selection represented another first for JPL: under the severe constraints of the pandemic, the traditional "site visit" by NASA's review committee took place virtually — but, as the outcome showed, no less successfully.



# EARTH SCIENCE

FROM EARTH'S IMMENSE ATMOSPHERE and ice sheets to its fragile deltas, the collection of data and the understanding of our planet as a system continues to drive innovative efforts to care for our planet, guiding the way forward for climate change, the water cycle, and natural hazards.



## PINPOINT MEASURES POWERED BY PHILANTHROPY



**AS THE WINDOW** to limit global warming closes further, scientists and policymakers have an urgent need for new technologies that can quickly and accurately identify large greenhouse gas emitters across the globe.

Carbon dioxide and methane make up approximately 80% of human greenhouse gas emissions. Current approaches to measure these emissions at the individual facility scale present challenges, especially in terms of transparency, accuracy, scalability, and cost.

Carbon Mapper, a pioneering satellite constellation program, will help overcome these challenges by pinpointing high-emitting sources. This data will greatly expand understanding and transparency of emissions for decision makers and civil society to accelerate action.

Powered by philanthropy, Carbon Mapper depends on a unique coalition of private and public sector teams to deploy a science-driven, sustained, and policy-oriented support service for maximum impact.

The coalition includes: JPL, to deliver the hyperspectral imaging spectrometer payload; Planet, operator of the world's largest fleet of Earth-imaging satellites, to deliver the spacecraft; California Air Resources Board, for policy leadership across California; High Tide Foundation, to lead the extensive philanthropic investment; University of Arizona and Arizona State University, for scientific leadership of data products; RMI, to guide methane use case applications for policy development; and Bloomberg Philanthropies, for its long track record of supporting solutions to fight climate change.

Carbon Mapper's satellite constellation will take to the skies in two phases.

Phase 1 is underway, with the first two satellites planned to launch in 2023. Phase 2 will deploy the world's first carbon-tracking multi-satellite constellation starting in 2025.

# EARTH'S MOONSHOT FOR CLIMATE CHANGE

**WITH THE CHALLENGES** of climate change growing by the season, JPL and NASA have redoubled their efforts to integrate research with policy.

NASA Administrator Bill Nelson and Deputy Administrator Pam Melroy affirmed this commitment during an Earth science roundtable convened by Administrator Nelson and held at JPL in the fall of 2021.

The roundtable focused on ways scientists, engineers, resource managers, and policymakers can work together to address climate challenges on our home planet.

“In truth, this discussion is about saving our planet,” Nelson said. “NASA is the point of the spear on climate change.”

Central to the discussion were JPL efforts to continue to address climate change. One of the main activities is growing our fleet of Earth orbiting instruments with new and important capabilities.

Efforts poised to launch in 2022 include:

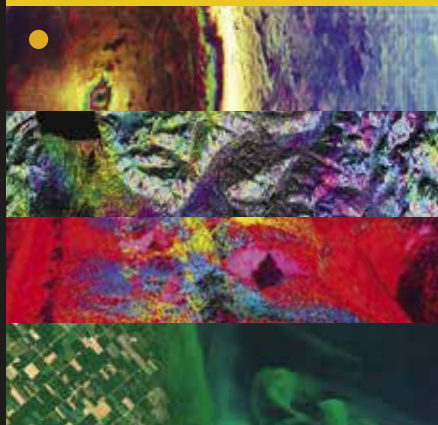
- Surface Water and Ocean Topography (SWOT), which will continue JPL’s observations of the water cycle and climate system
- Earth Surface Mineral Dust Source Investigation (EMIT), which will assess the regional and global heating and cooling effects of mineral dust

In 2023-24:

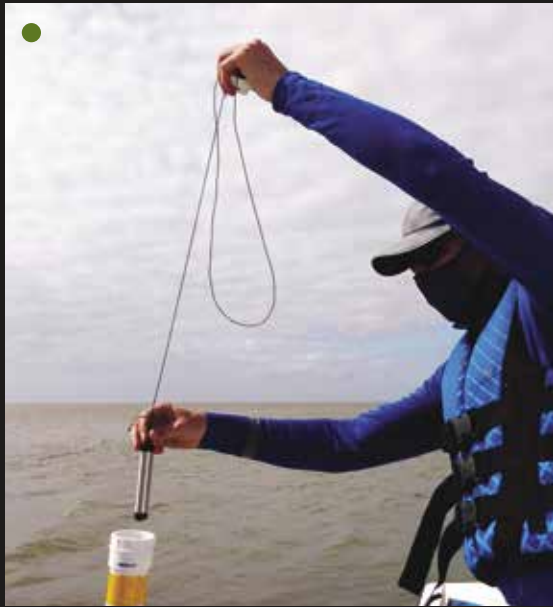
- NASA-ISRO Synthetic Aperture Radar (NISAR), a partnership with the Indian Space Research Organization, which will track subtle changes to Earth’s surface to mitigate the threat of natural hazards and climate change
- Multi-Angle Imager for Aerosols (MAIA), which will provide a better understanding of the connections between air pollution and human health

These missions will become part of NASA’s Earth System Observatory, a new set of Earth-focused missions to guide efforts related to climate change, by working together to create a 3D, holistic view of Earth, from bedrock to atmosphere.

In preparation for the next era, JPL is continuing to collaborate with federal, state, and commercial organizations to convert datasets into applications to care for our planet. JPL plans to increase access and use of datasets by embracing technologies, including artificial intelligence, to better enable data-driven science with an increasing emphasis on climate change.



With its solar panels deployed, the SWOT spacecraft undergoes its integration and test engineering phase.



## EARTH MISSION EBB AND FLOW

**2021 WAS A YEAR OF BEGINNINGS** and endings for several key JPL missions and projects.

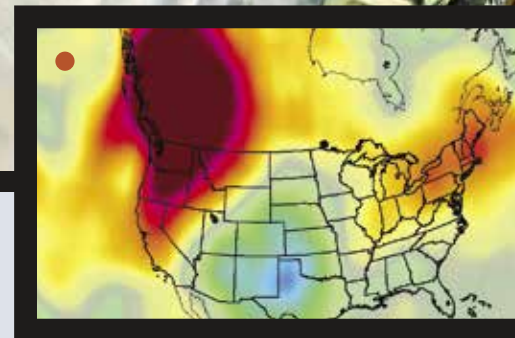
Investigation of Convective Updrafts (INCUS) won funding in 2021 and is expected to launch in 2027. This collection of three small satellites will focus on the vertical transport of air and water vapor through storms, one of the great unknowns in weather and climate science.

Observation Products for End-Users from Remote Sensing Analysis (OPERA) was funded through 2025 to develop globally-applicable products to inform decision-makers from federal agencies and the science community for a broad range of applications related to disasters, resource management, and monitoring.

Space Test Program-Houston 8 (STP-H8) launched to the International Space Station in late 2021 to demonstrate new lower-priced weather-forecasting technology. If the technology operates as expected, organizations could launch four or five satellites for the current cost of one. More satellites increase the accuracy of life-saving forecasts of weather-related disasters.

The hugely influential Oceans Melting Greenland (OMG) airborne campaign completed its mission in 2021. OMG confirmed the ocean's role in melting Greenland's ice from below the sheet and strengthens the accuracy of predicting ice discharge from Greenland by a factor of 50%. OMG also revolutionized our picture of ocean floor maps that will pave the way for better predictions on how Greenland's glaciers will continue to retreat.

Delta-X, which studied how and why land is sinking around river deltas, also successfully completed the data collection phase of its mission. Delta subsidence, mostly caused by human activities, puts more than half a billion people in peril because the rate of sinking can dwarf the speed of sea level rise. Delta-X data will create a model that can be applied globally, giving us a glimpse of the future of deltas and how to take action.



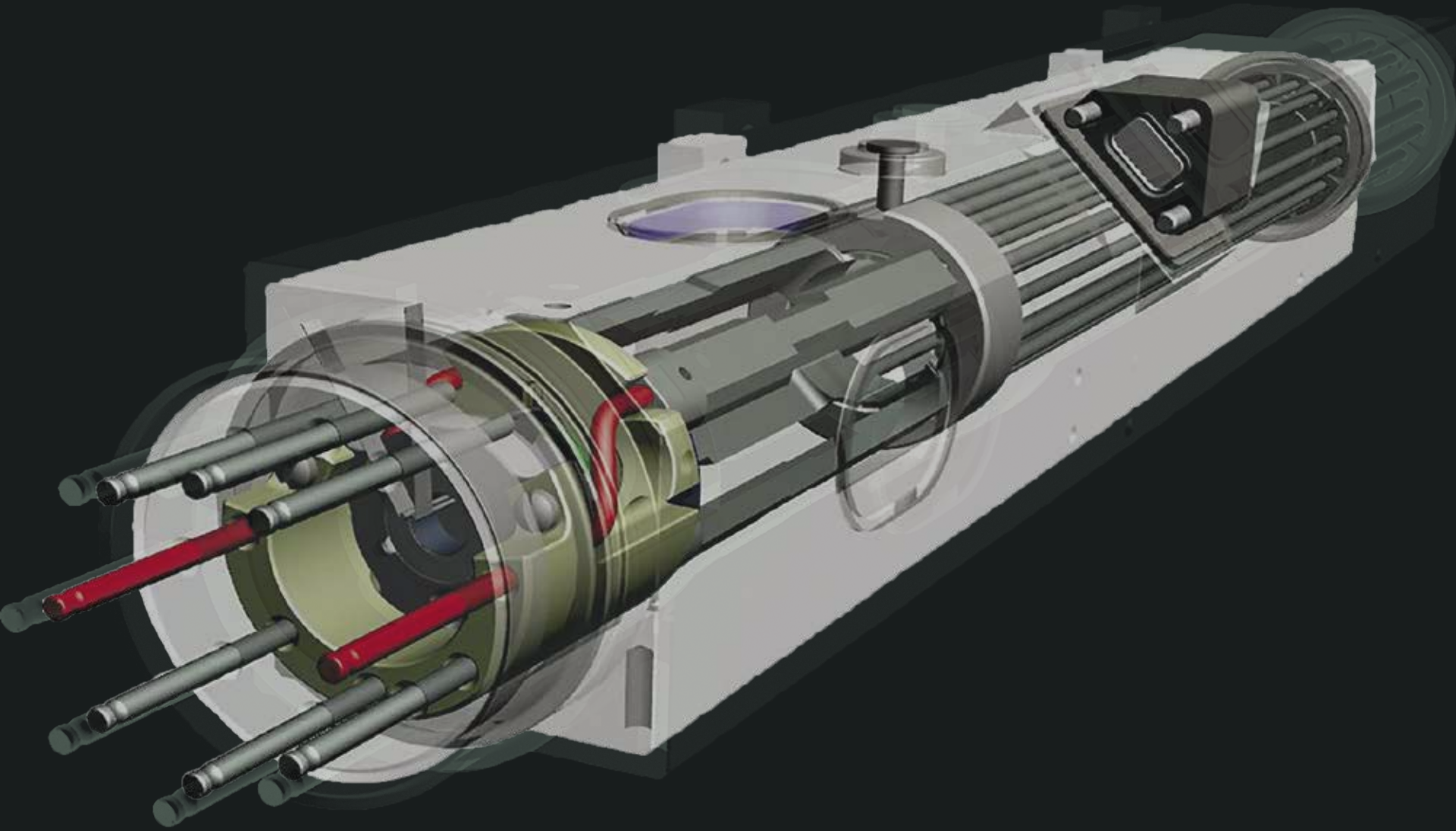
## CAPABILITIES THAT TRANSFORM OUR WORLD

**JPL CONTINUED ITS ROBUST** set of collaborations with government agencies and private-sector sponsors to address problems of national significance and catalyze economic growth. JPL realizes that many of its technologies and capabilities that are critical to exploring space can also be made available to solve challenging problems on Earth, thus providing a benefit to our nation and society at large. These benefits include new commercial products that improve quality of life, create new jobs, and generate new small business suppliers for NASA missions.

Highlights include:

- Commercial licensing activity resulted in 16 new patent and software licenses, including nine patent licenses, five software licenses, and two new Covid VITAL ventilator licenses.
- 45 JPL software packages were disseminated in open source licenses.
- New commercial space licenses were entered into with startup Toofon, Maxar, H2U, and iSpace.





# TECH NOLOGY

**SPACE EXPLORATION IS DRIVEN BY** innovations rooted in new technology development to advance mission objectives. At JPL, our technology capabilities allow us to expand our knowledge and understanding of the universe in the service of our nation, and humanity as a whole.



# GOING DEEP FOR THE RECIPE OF LIFE

**OUR SUN IMMERSSES** living things in ultraviolet light (UV) all day long, but to find out what makes them more than things, scientists need a particular type of UV.

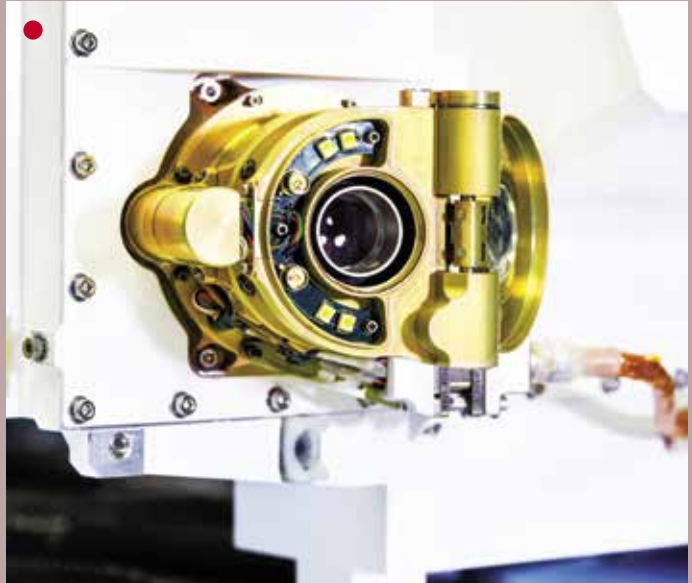
Spectroscopy instruments that can determine the vibrational modes of individual molecules — revealing the ingredients of the recipe for life — require what is known as deep UV light.

Traditionally, gas lasers have made the deep UV for this kind of science, but they are bulky and fragile, and not well-suited to the harsh environment of spaceflight. Instead, JPL is developing a micro-chip-scale, solid-state deep UV laser that will be about 100 times smaller and up to 10 times more powerful.

Why isn't such a laser already in use? For one thing, achieving such an increase in power on a vastly reduced scale requires skilled manipulation of beta-barium borate crystals, a notoriously challenging material.

JPL's new fabrication process on a sub-micron scale results in deep UV-range photonic components that serve as light sources for in-situ instruments, allowing the nondestructive compositional analysis of organics, biosignatures, and other chemical attributes that make up the recipe of life.

The deep UV laser is expected to serve a wide variety of future space missions, offering dramatically improved analysis of samples both on Mars and in the oceans under the icy moons of the outer solar system — all prime targets in the search for extraterrestrial life.





## A CADRE OF POSSIBILITIES

**ANOTHER SMART SYSTEM** — a flock of shoe-box-sized, autonomous scouting robots to explore lunar and planetary terrain — is under development through NASA's Cooperative Autonomous Distributed Robotic Explorers (CADRE) project.

CADRE robots will have the intelligence and autonomy to explore independently, while operating as a smart multiple-robot network.

They will be instructed to explore specific targets, returning data in occasional batches, with instructions for future operations relayed from the parent lander. This will reduce dependency on communication with Earth — a critical issue when dealing with future, distant solar system missions.

Sharing knowledge between the multiple robots can be as simple as sharing position and map knowledge to improve their path planning and location of science targets.

However, it can also open a new world of science exploration by sharing science sensor data.



For example, by using a multi-agent system with ground-penetrating radar, the data from different rovers can be used to create subterranean maps. Similarly, multiple rovers armed with seismic sensors could spread out to provide a better understanding of lunar conditions below the surface.

CADRE technology is slated for lunar tests under NASA's Commercial Lunar Payload Services (CLPS) initiative. Eventually, fleets of small, self-aware mini-rovers may explore wide-ranging areas on the Moon, Mars, and the icy moons of the outer solar system — a force multiplier for science return.

While on the Moon or on dry planets, rovers big and small will need a way to brush off alien dust that can build up rapidly. A new JPL technology demonstrated on the Perseverance rover uses compressed nitrogen gas to clear dust from Martian samples. The lunar and planetary version of this “dustbuster,” currently in development, will be self-contained and scalable to remove surface dust using a variable-strength flow of gas.



## AN EXTRA “A” FOR PLANETARY ROVERS

**DUE TO THE EXTREME DISTANCE** between Earth and Mars, averaging 140 million miles, radio commands can take as long as 24 minutes to reach robotic explorers on the Red Planet.

What if these robotic explorers could think for themselves? What if they could perform more rapidly and independently?

A team of JPL engineers is developing the Machine Learning-based Analytics for Automated Rover Systems (MAARS) suite of machine-learning tools to usher in a new era of planetary exploration, enabling rovers and their earthbound team to work with more accuracy and efficiency than ever before.

Using our Athena rover testbed, the MAARS system autonomously drove twice as fast as the Perseverance rover on Mars — and with a keener eye. Where today's rovers may miss important details because they were not specifically commanded to look for them, MAARS is designed to scan the surrounding terrain for opportunistic science.

In the near future, smart systems like MAARS will allow us to develop safe and efficient robotic explorers that will act not just as tools, but as essential partners in planetary exploration.



## TIME IS ON OUR SIDE

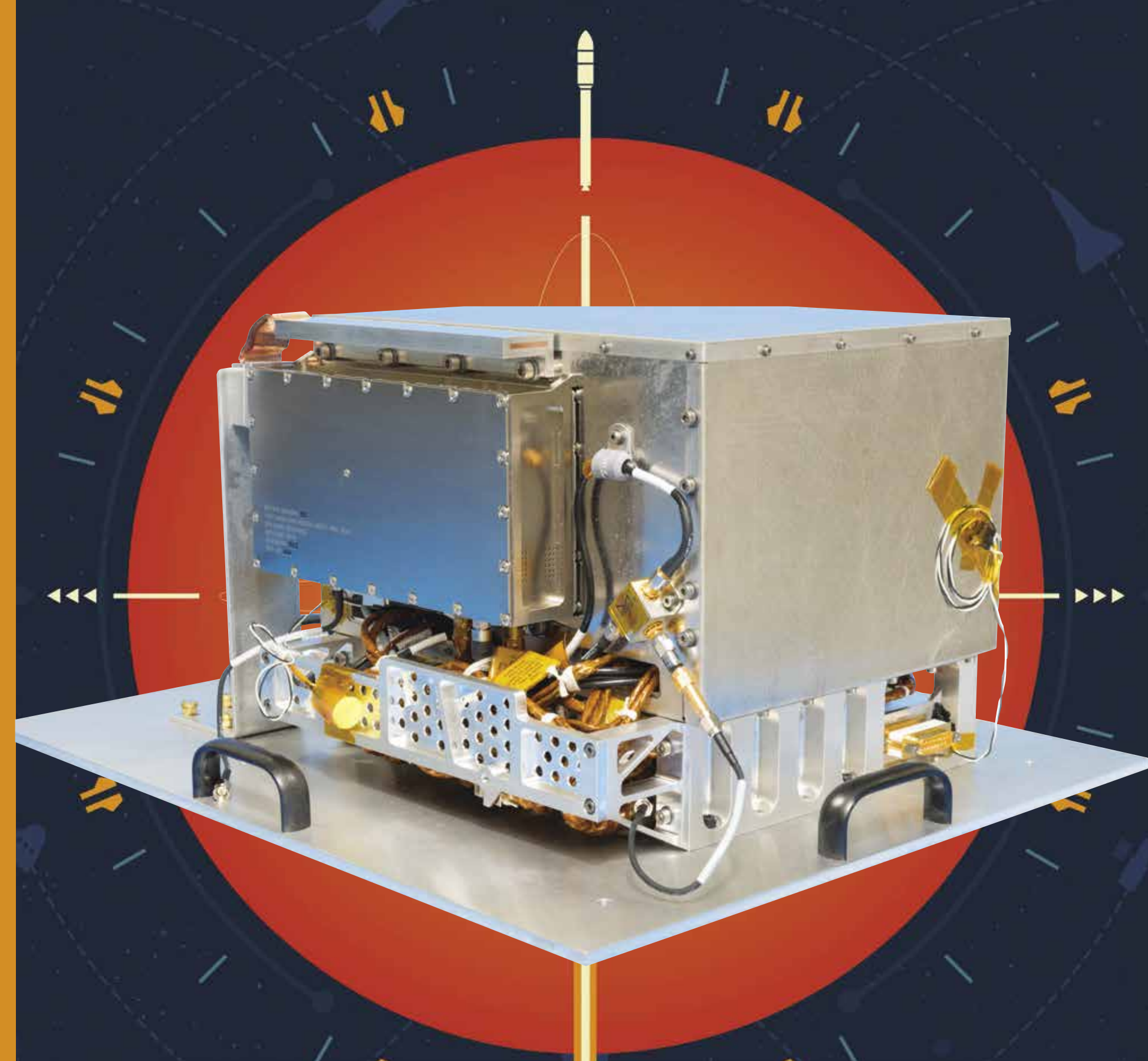
**AN ACCURATE TIMEKEEPER**, one that can be carried onboard a spacecraft, is essential as we explore more deeply into space.

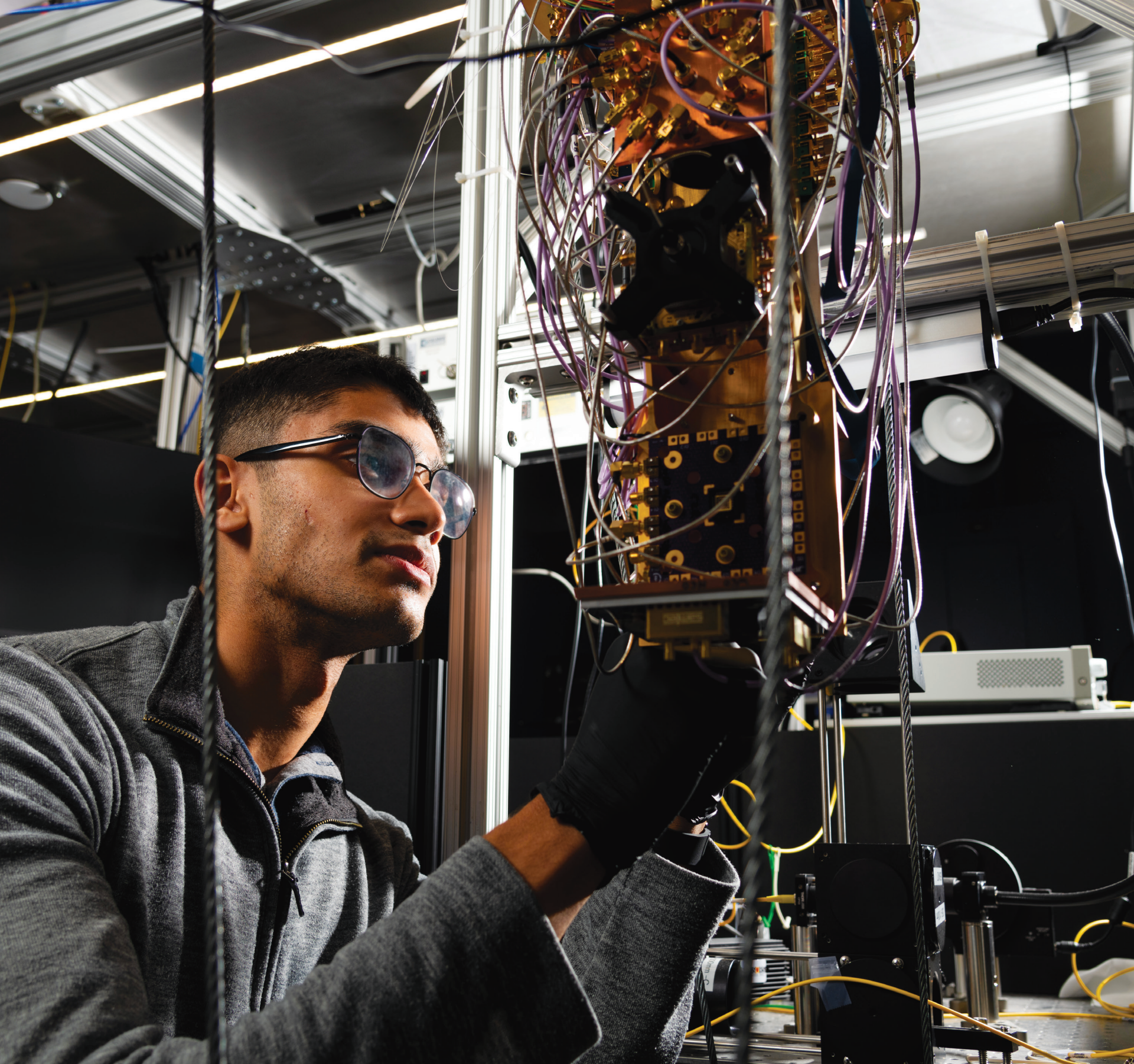
A timekeeper needs to achieve precision within billionths of a second to determine a spacecraft's position to within one meter. Compounded over hundreds of measurements over months of spaceflight, such precision — or its absence — could mean the difference between success and failure.

Knowing the time on Earth has never been easier, as our timekeepers, such as smart watches and phones, reference extremely precise atomic clocks. Unfortunately, accurate atomic clocks on Earth can be as big as refrigerators, requiring far too much volume, mass, and power for spacecraft.

To solve this, JPL technologists led development of a Micro Mercury Trapped Ion Clock, less power-hungry and 1,000 times more accurate than its best commercially available counterpart — and barely bigger than a cube-shaped quart container.

Miniaturizing and making atomic clocks more precise will allow even the smallest spacecraft and deep space probes to navigate autonomously with unprecedented precision.





# CAMPUS & LAB

**CALTECH SCIENTISTS AND ENGINEERS** at campus and JPL, which Caltech manages for NASA, pooled their talent and expertise to make strides in wide-ranging research and development areas, including balloon-based detection of venusquakes; mutable material inspired by chain mail; the atmospheric effects of pandemic-related reductions in emissions; and prediction of ocean currents under the ice of Saturn's moon Enceladus.



## BALLOONS FOR HUNTING VENUSQUAKES

**A TEAM OF CALTECH** researchers from campus and JPL are partnering with colleagues at Sandia National Laboratories to explore the possibility of sending balloons to Venus to hunt for quakes and reveal secrets of its interior.

In a study published in *Geophysical Research Letters* in June 2021, the team described how balloons equipped with science instruments could help reveal the innermost mysteries of Venus, a rocky world where surface temperatures are hot enough to melt lead and atmospheric pressures are high enough to crush a submarine.

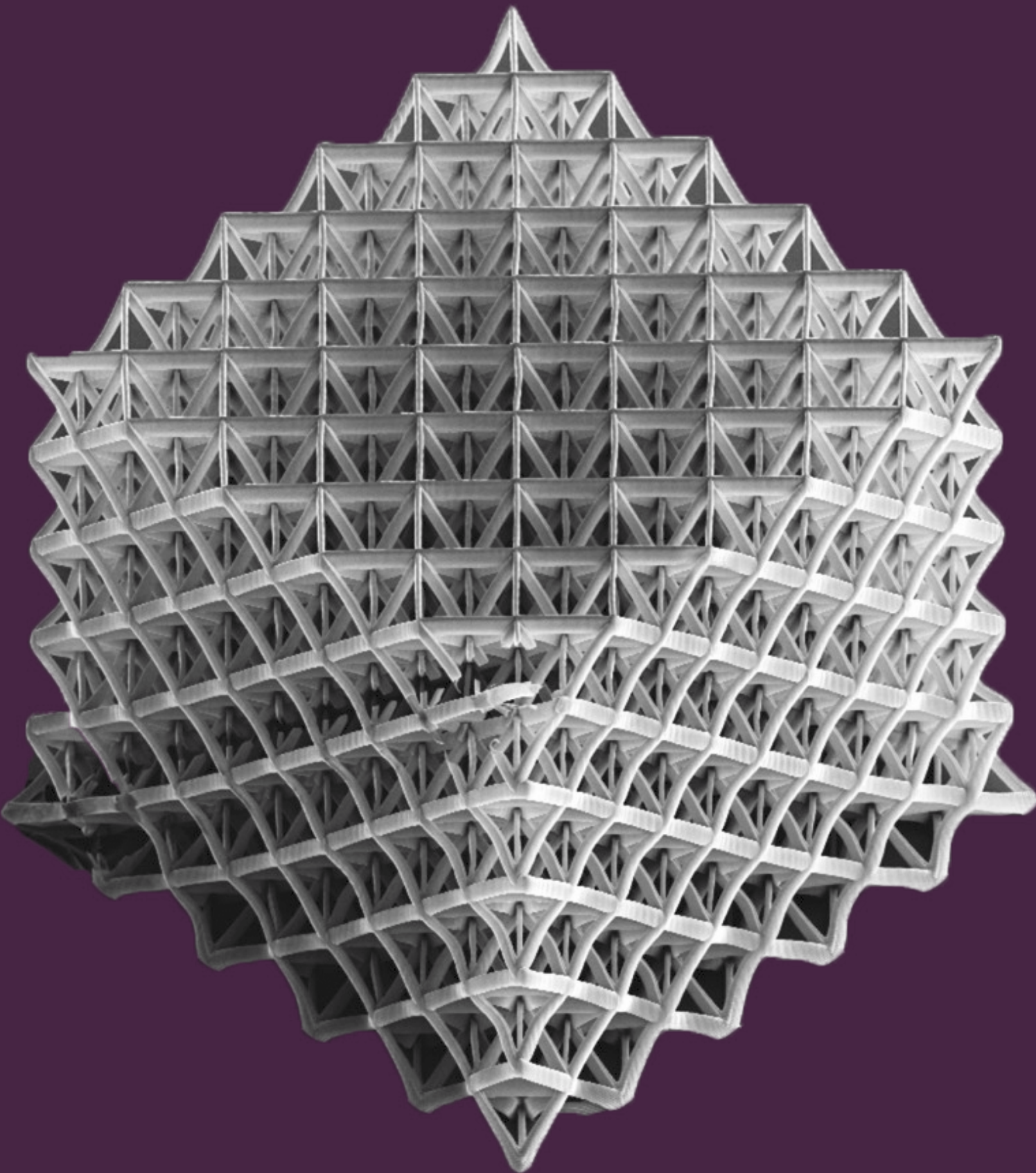
The researchers achieved a milestone in July 2019 when they used balloon-based barometers (instruments that measure changes in air pressure) to “hear” the low-frequency sound waves caused by an after-shock of a series of powerful earthquakes that rumbled near Ridgecrest, California. This was the first balloon-borne detection of a naturally occurring earthquake.

Given Venus’ extreme environment, scientists can’t use ground-based seismometers. But seismic waves produce sound waves, which can be studied from the air. Because of the denser Venusian atmosphere, balloons carrying science instruments, flown in its cool layers at altitudes between about 31 to 37 miles (50 to 60 kilometers), should be able to detect venusquakes, volcanic processes and outgassing events.

Study authors include Caltech’s Quentin Brissaud (lead), also affiliated with the Norwegian Seismic Array; Caltech’s Jennifer M. Jackson; JPL’s Siddharth Krishnamoorthy and Attila Komjathy; and Sandia National Laboratories’ Daniel Bowman.



One of the experimental balloons being prepared for flight



## MATERIALS THAT CHANGE STIFFNESS ON COMMAND



**ENGINEERS AT CAMPUS** and JPL have developed a material inspired by chain mail that can transform from a foldable state into specific solid shapes under pressure. The goal, according to Caltech professor Chiara Daraio, is to “create a fabric that goes from soft and foldable to rigid and load-bearing in a controllable way.”

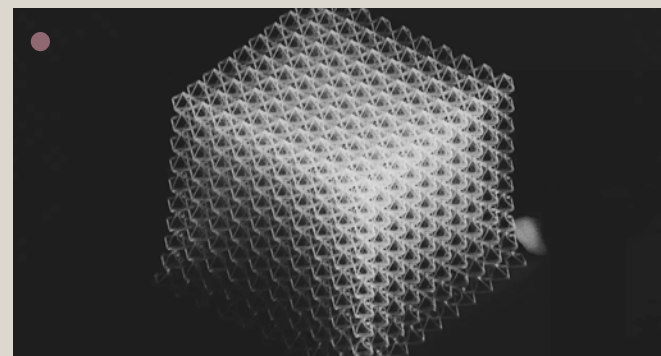
The material has potential applications as a smart fabric for exoskeletons, or as an adaptive cast that adjusts its stiffness over the healing course of an injury, or even as a deployable bridge that can be unrolled and stiffened.

It turns out that sheets of linked rings (and other shapes) can jam together under both compression and tension (when pushed together or pulled apart), becoming stiffer and able to bear loads.

Members of the team designed several configurations of linked particles of different shapes, then 3D-printed the materials out of polymers and metals.

The engineers stressed the fabrics by using a vacuum chamber or dropping a weight to control the jamming of the materials. In one experiment, a chain-mail fabric was able to support more than 50 times its own weight.

One application is smart wearable equipment. “When unjammed, [the fabrics] are lightweight, compliant, and comfortable to wear; after the jamming transition, they become a supportive and protective layer on the wearer’s body,” said former Caltech postdoctoral researcher Yifan Wang, now an assistant professor at Nanyang Technological University in Singapore, and co-lead author of a paper describing the materials that was published in *Nature* in August 2021.



● Under pressure, the chain-mail-inspired material can go from foldable and fluid-like to a solid shape.

● When stiffened, the material is able to act as a sturdy bridge.

● A coated polymer truss prior to etching



## LOWER PANDEMIC EMISSIONS HAD SURPRISING RESULTS

**WORLDWIDE RESTRICTIONS** during the Covid-19 pandemic caused huge reductions in travel and other economic activities, drastically decreasing air pollution and greenhouse gas emissions within just a few weeks.

However, a new survey of the effects of the pandemic on the atmosphere, using satellite data from NASA and other international space agencies, reveals some unexpected findings.

Published in the *Proceedings of the National Academy of Sciences* in November 2021, the study grew from a workshop sponsored by Caltech's W.M. Keck Institute for Space Studies, led by scientists at campus and JPL.

The most surprising result, the authors noted, is that while carbon dioxide emissions fell by 5.4% in 2020, the amount of CO<sub>2</sub>, an important greenhouse gas, continued to grow in the atmosphere at about the same rate as in preceding years.

Another surprise: although Covid-related drops in emissions of nitrogen oxides, an important pollutant, quickly led to a global reduction in ozone, the drop in NO<sub>x</sub> also limited the atmosphere's ability to cleanse itself of methane, another gas that traps heat in the atmosphere. In 2020, methane concentration grew by 0.3% — a faster rate than at any other time in the last decade.

“To understand what is driving changes to the atmosphere, we must consider how air quality and climate influence each other,” said Joshua Laughner, lead author of the study and a postdoctoral fellow at Caltech.

## CHURNING ON ENCELADUS

**ACCORDING TO CALTECH** researchers at campus and JPL, the subsurface ocean on icy Enceladus — one of Saturn's moons — might be churning with currents similar to those on Earth. Because it has liquid water, this moon figures prominently in the search for signs of life.

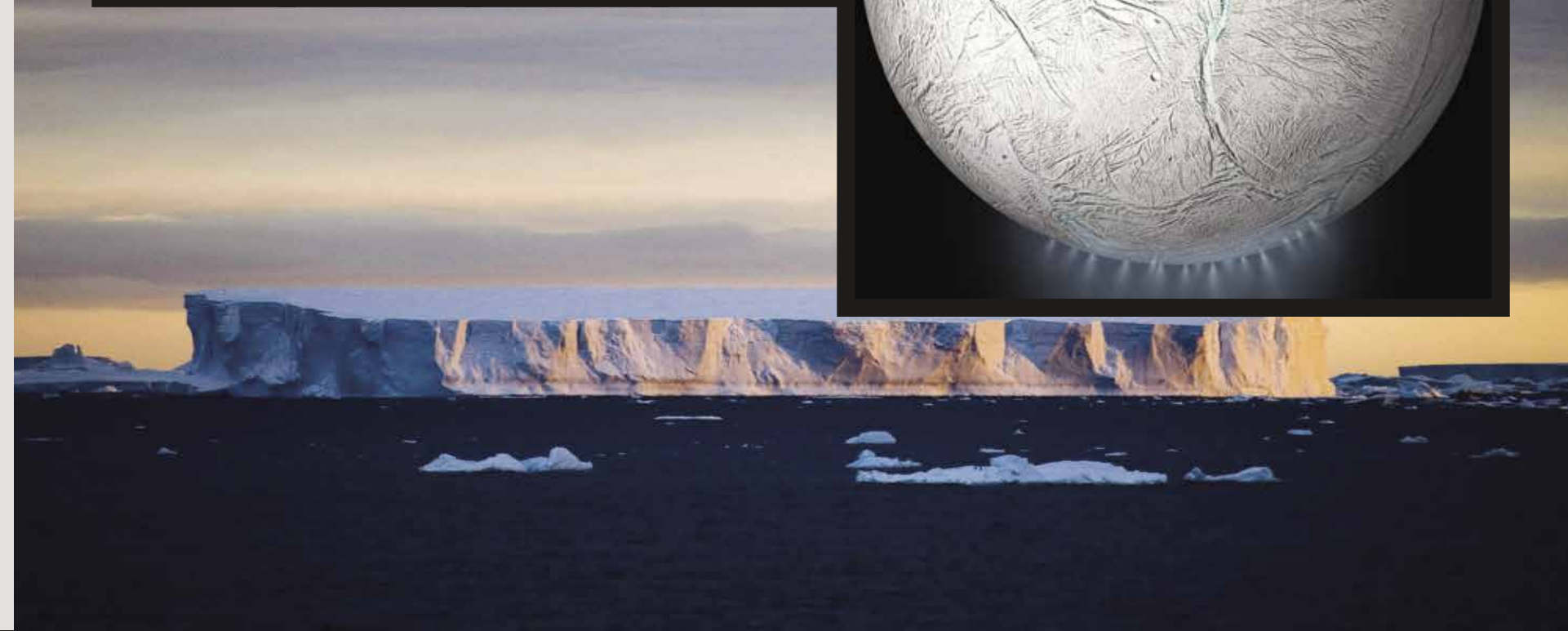
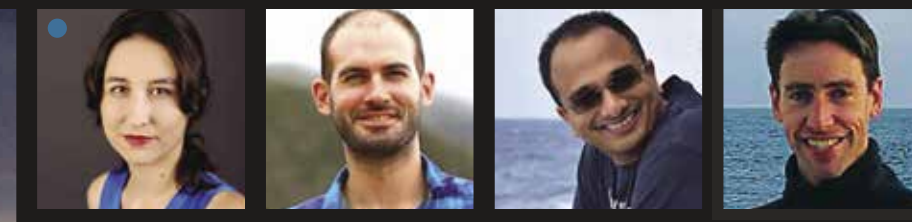
Although very different, the oceans of Enceladus and Earth share one important quality: they are salty. Variations in salinity could drive the ocean circulation on Enceladus, much as they do in Earth's Southern Ocean, which surrounds Antarctica.

Measurements from the Cassini spacecraft have already revealed that Enceladus' ice shell is thinner at the poles than at the equator. According to the Caltech-JPL researchers, regions of thin ice at the poles are likely associated with melting and regions of thick ice at the equator

with freezing. This would affect the ocean currents because when salty water freezes, it releases the salts and makes the surrounding water heavier, causing it to sink. The opposite happens in regions of melt.

Based on computer modeling, the team's findings suggest that Enceladus' regions of freezing and melting would be connected by the ocean currents. This would create a pole-to-equator ocean circulation influencing the distribution of heat and nutrients. Understanding which regions of the moon's global ocean might be the most hospitable to life could help shape future missions.

Caltech's Ana Lobo and Andrew Thompson collaborated with JPL's Steven Vance and Saikiran Tharimena on the Enceladus study, which appeared in *Nature Geoscience* in March 2021.







# COMMS & ED

**IN THE SECOND YEAR OF THE PANDEMIC,** Communications and Education Directorate members rose to the challenges — and opportunities — of engaging the world virtually, leveraging digital tools and expertise to bring the excitement of JPL missions to record audiences across the globe.

## FOLLOWING HISTORY-MAKERS ON MARS

**WHILE THE PERSEVERANCE ROVER** and the Ingenuity helicopter were making history on Mars, Communications and Education teams rolled out a virtual red carpet, allowing worldwide fans to join these heart-pounding moments on their device of choice.

As part of the #CountdownToMars landing campaign, members of the public became virtual guests at Mars 2020 entry, descent and landing activities. They connected with like-minded space enthusiasts; asked questions of the experts; hung out at the livestreamed landing event; took souvenir photos with the Mars Photo Booth; and had the opportunity to send their name to Mars on a future mission.

For Ingenuity's first flight on April 19, 2021, the public enjoyed a front-row seat during a livestream as the mission team received confirmation in the JPL Space Flight Operations Facility that the helicopter had executed its aerial maneuvers successfully. Cheers erupted in the control room, and spread across the internet as flight photos from Ingenuity and Perseverance appeared on monitors.

News briefings, social media activities, and digital press kits on mission operations helped to connect audiences with history-making events on Mars throughout the year. The Mission to Mars Student Challenge, with over 100 activities and events, engaged more than a million students.

When Perseverance touched down on Mars on February 18, more than half of all NASA website traffic for the day went to mars.nasa.gov. According to NASA Headquarters, the two-day landing coverage had an estimated reach of billions, including the front pages of 157 newspapers. For 2021, Perseverance and Ingenuity were the top drivers of social media engagements on JPL channels.



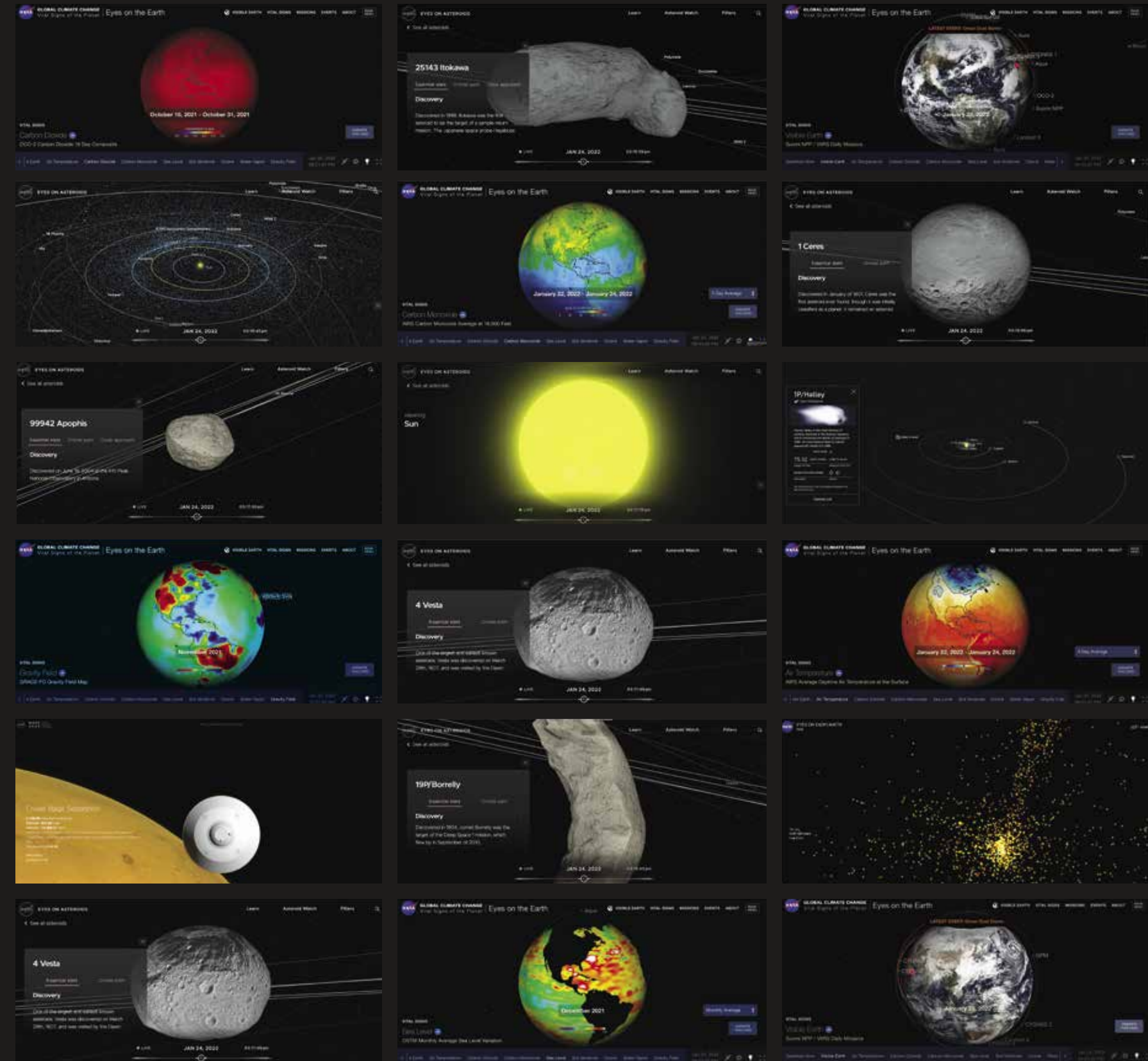


# EYES EVERYWHERE

**NASA'S EYES**, a Communications and Education-led venture at [eyes.nasa.gov](https://eyes.nasa.gov), offers immersive experiences through 3D, real-time visualizations of Earth, our solar system, the universe, and the spacecraft that explore them. Armchair astronauts can navigate the cosmos with their smartphone, tablet or computer.

The site's latest web-based app, NASA's Eyes on Asteroids, which went live in December, provides 3D views of the roughly 28,000 asteroids and comets that approach Earth's orbital neighborhood.

2021 saw an explosive growth in the popularity of these data-driven visualizations. The website garnered almost 44 million page views, an increase of 42% over the previous year, making it the fifth most-viewed NASA website.



18 views as seen by NASA's Eyes

# VIRTUAL FIRSTS



**CHALLENGED BY COVID CONSTRAINTS**, innovators in Communications and Education helped to devise new ways to deliver rich and compelling online experiences.

Led by the Formulation Science Communications Office, a directorate strategic partnership with the Office of Formulation, JPL's video and design teams created an interactive, compelling virtual environment to support critical site visits for two of NASA's Discovery-class planetary missions concepts: VERITAS and Trident.

These innovators converted a JPL cafeteria into a soundstage with multiple sets while conforming to all Covid protocols. Remote presenters from across the U.S. and Europe seamlessly presented content, animations and nearly 50 short videos to demonstrate they were the right teams for NASA.

The payoff: NASA selected the VERITAS team to fly a mission to Venus.

Mission site reviewers were not the only ones with inside access.

Employing an online format for the first time, JPL hosted the Los Angeles regional competition in both the National Science Bowl and National Ocean Sciences Bowl in 2021.

These bowls, coordinated by the U.S. Department of Energy and the Consortium for Ocean Leadership, respectively, encourage the academic growth and development of high school students.

A total of 27 teams representing local schools vied for first place in the regional competitions, answering complex science and math questions. The regional winners were Irvine's University High School in the National Science Bowl, and Santa Monica High School in the National Ocean Sciences Bowl.

## 2021 INTERNS



## NATIONAL OCEAN SCIENCES BOWL WINNERS



## NATIONAL SCIENCE BOWL WINNERS



Top: expanding diversity in STEM interns; Middle and bottom: winning teams from Santa Monica High School and Irvine's University High School.



## BUILD IT AND THEY WILL COME

**ALTHOUGH THE PANDEMIC** shut down in-person tours at JPL, Guest Services and Media Relations teams responded by creating two virtual tour experiences to ensure public and educational groups had access to the JPL campus.

One experience is virtually hosted by a JPL tour guide and allows visitors to enjoy a 360-degree look at key JPL locations such as Mission Control and the Spacecraft Assembly Facility.

In 2021, there were over 400 group tours, engaging more than 14,000 visitors.

The second experience is a self-service option allowing visitors to select and navigate their own tours. This opened the Lab for the first time to a global audience and increased connections with underserved communities and minority-serving institutions.

In 2021, over 60,000 people took self-guided tours.



## WEBBY KUDOS

**NASA RECEIVED THREE WEBBY AWARDS** and was honored as the People's Voice winner in two categories in the 2021 Webby Awards competition. The awards, given by the International Academy of Digital Arts and Sciences, recognize the best in online communications.

Public Engagement teams manage or co-manage two of the winning sites: Exoplanet Exploration, investigating the science of planets outside our solar system, which won for Website and Mobile Site: Science; and Eyes on the Earth, showing global climate change in real time, the winner for Website and Mobile Site: Data Visualization.

In addition, NASA's flagship social media accounts won for Best Overall Social Presence: Brand.

## AMBASSADORS FOR NASA



**THE SOLAR SYSTEM AMBASSADORS**, a NASA volunteer program aimed at raising public awareness of space exploration, had plenty to celebrate in 2021.

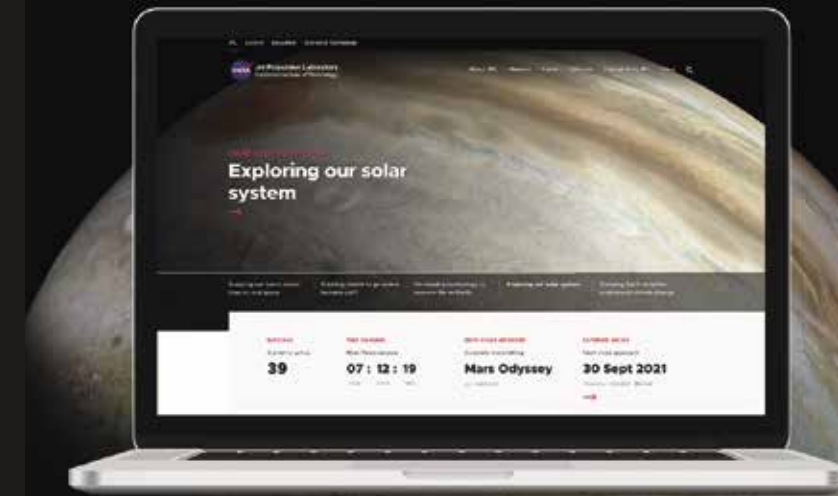
The JPL-originated program observed its 25-year anniversary while notching impressive milestones. Since 1997, the volunteer ambassadors have organized 55,000 public outreach events reaching over 11 million people. From its roots as a volunteer educators' group sharing Galileo mission information and science, the program has grown to include over 1,000 volunteers (many from outside the education profession) located in all 50 states, Puerto Rico, and U.S. military bases and consulates overseas.

Even before Covid-19, the volunteers were connecting with the public in diverse ways — from in-person talks at schools and festival exhibits, to television interviews, podcasts and social media events.

The pandemic led to a focus on virtual events, including partnering with libraries across the country. Moving forward, the plan is to provide ambassadors with training on best practices for conducting hybrid programs.

## A NEW LOOK FOR JPL ONLINE

**JPL'S FLAGSHIP PUBLIC WEBSITE** was thoroughly revamped in 2021. The redesign depicts a more holistic view of the Lab, emphasizing its identity as an elite hub of robotic space exploration while also highlighting the culture, people and history that make it unique. An external audience research study validated that the redesign effectively conveys this richer picture of JPL. The new site runs on an improved content management system that will meet the Lab's online communication needs for years to come. Communications and Education collaborated with the Information and Technology Solutions Directorate on the web project.



# MAJOR CONTRACTOR PARTNERS

## **APPLIED PHYSICS LABORATORY, THE JOHNS HOPKINS UNIVERSITY**

Europa Clipper, Mars Reconnaissance Orbiter, Psyche

## **BALL AEROSPACE & TECHNOLOGIES CORPORATION**

CloudSat, NEOSurveyor, NEOWISE, SPHEREx

## **COLUMBUS TECHNOLOGIES AND SERVICES INCORPORATED**

Labor Support Services

## **MANTECH ADVANCED SYSTEMS**

Institutional Computing

## **PERATON, INC.**

Deep Space Network Operations, Mars 2020

## **RAYTHEON**

Engineering, Implementation, Science, Operations and Communications

## **LOCKHEED MARTIN CORPORATION**

Europa Clipper, InSight, Juno, Mars Odyssey, Mars Reconnaissance Orbiter, Mars Sample Return, VERITAS

## **MORI ASSOCIATES, INC.**

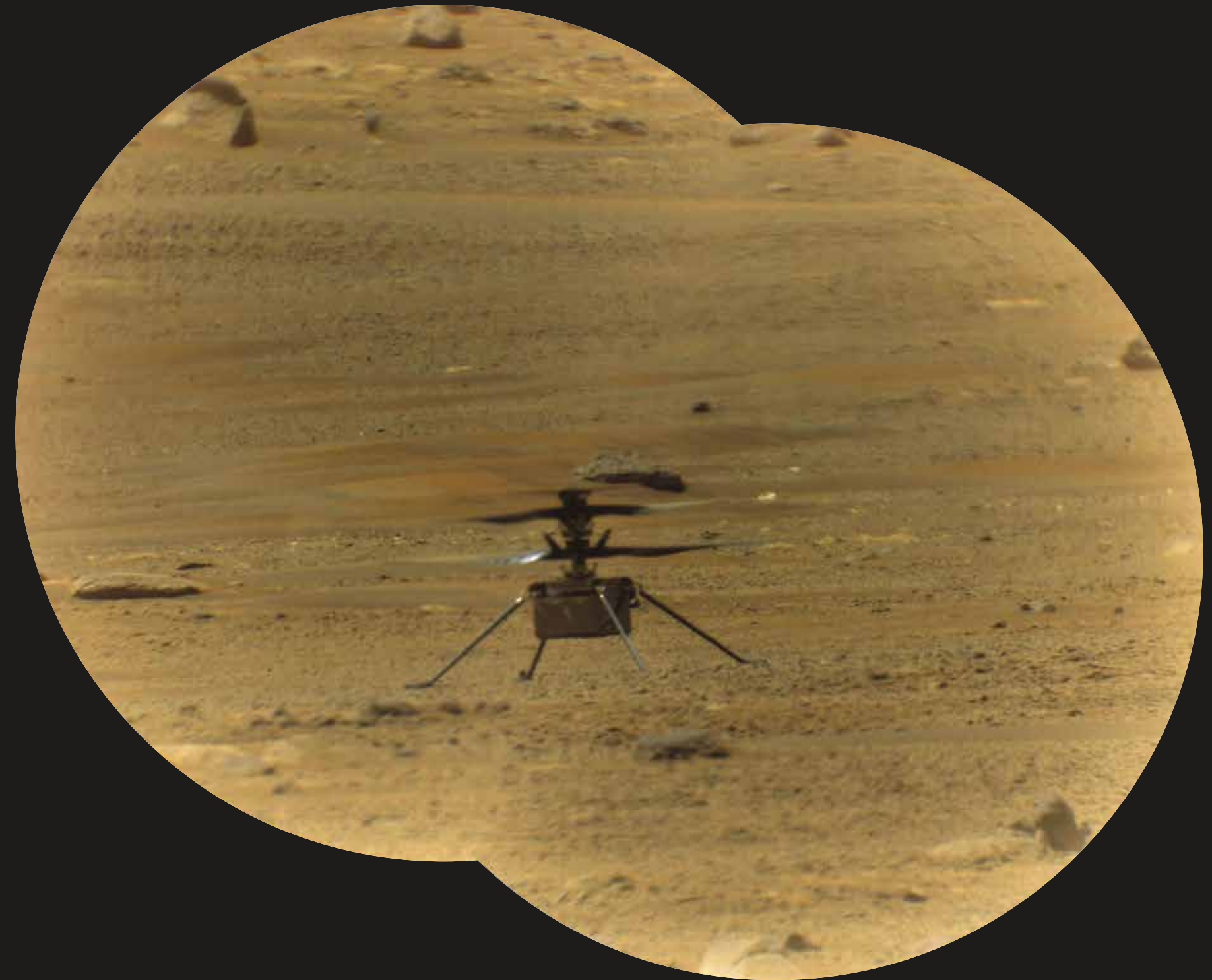
Information Technology Infrastructure Support

## **SOUTHWEST RESEARCH INSTITUTE**

EMIT, Europa Clipper, Mars Science Laboratory

## **EMCOR GOVERNMENT SERVICES**

Facilities Maintenance and Operations



Ingenuity viewed from Perseverance on May 14, 2021, the 82nd Martian day, or sol, of the mission.

# MAJOR EXTERNAL AWARDS

## SURENDRA ADHIKARI

American Geophysical Union (AGU)  
John Wahr Early Career Award

## YOSEPH BAR-COHEN

The International Society for Optics and Photonics (SPIE) Founding Chair Award

## LAURIE BARGE

Scialog: Signatures of Life in the Universe Research Funding

## BOBBY BRAUN

National Space Society 2021 Space Pioneer Award

## NACER CHAHAT

Institute of Electrical and Electronics Engineers (IEEE) Fellow  
Institution of Electronics and Telecommunication Engineers (IETE) 2021 Dr. Sudhakar Rao Award

## COMMUNICATIONS & EDUCATION

### DIRECTORATE

Webby Awards:  
Website and Mobile Site: Science — Exoplanet Exploration  
Website and Mobile Site: Data Visualization — Eyes on the Earth

## ANDREA DONNELLAN

American Geophysical Union (AGU) Fellow

## MICHAEL GROSS

American Institute of Aeronautics and Astronautics (AIAA) International Cooperation Award

## FRED HADAEGH

American Institute of Aeronautics and Astronautics 2021 (AIAA) Mechanics and Control of Flight Award

## CHRISTINA HERNANDEZ

Hispanic Heritage Foundation 2021 STEM Award

## JPL

International Astronautical Federation 3G Diversity Award

Forbes Best Place to Work in California list  
IDG's Insider Pro and Computerworld 2021 Best Place to Work in IT list #38 among large companies

## ALAN KLEINSASSER

Institute of Electrical and Electronics Engineers (IEEE) Fellow

## AKSHATA KRISHNAMURTHY

Space and Satellite Professionals International "20 under 35"

## GENTRY LEE

Elected to National Academy of Engineering

## RANDI LEVIN

2021 SoCal CIO of the Year/ORBIE Winner, Large Corporate

## ROB MANNING

National Space Society 2021 Space Pioneer Award

## MARS INGENUITY HELICOPTER

Aviation Week Laureate Award  
National Space Foundation John L. "Jack" Swigert, Jr. Award for Space Exploration  
National Space Club & Foundation Goddard Trophy

## MARS INGENUITY HELICOPTER

### FLIGHT TEAM

American Institute of Aeronautics and Astronautics (AIAA) Space Systems Award

## MARS INGENUITY HELICOPTER

### NAVIGATION TEAM

Royal Institute of Navigation Duke of Edinburgh Award

## MAVEN FLIGHT TEAM (MARS ATMOSPHERIC AND VOLATILE EVOLUTION)

International Space Ops Award for Outstanding Achievement (from 2020)

## IOANNIS MIKELLIDES

American Institute of Aeronautics and Astronautics (AIAA) Fellow

## SHOULEH NIKZAD

The International Society for Optics and Photonics (SPIE) Aden and Marjorie Meinel Technology Achievement Award  
SPIE Luminary

## CLARA O'FARRELL

Hispanic Heritage Foundation 2021 STEM Award

## JAMES POLK

American Institute of Aeronautics and Astronautics (AIAA) Fellow

## STAN SANDER

American Geophysical Union (AGU) Fellow

## HUI SU

American Meteorological Society Fellow

## DIANA TRUJILLO

Hispanic Heritage Foundation 2021 STEM Award

## MICHAEL WATKINS

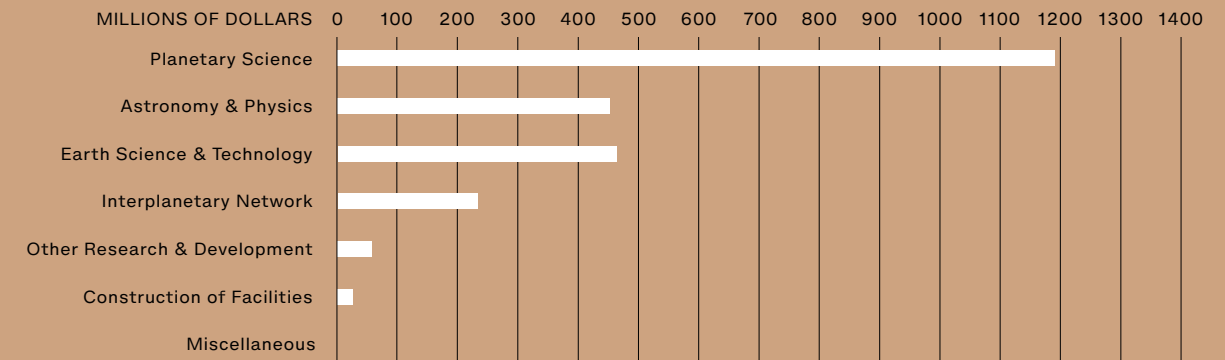
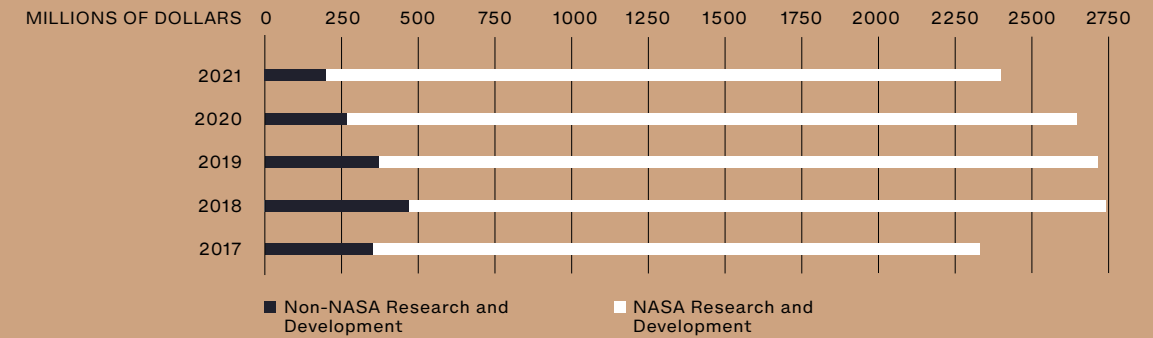
American Institute of Aeronautics and Astronautics (AIAA) International Cooperation Award

## AARON YAZZIE

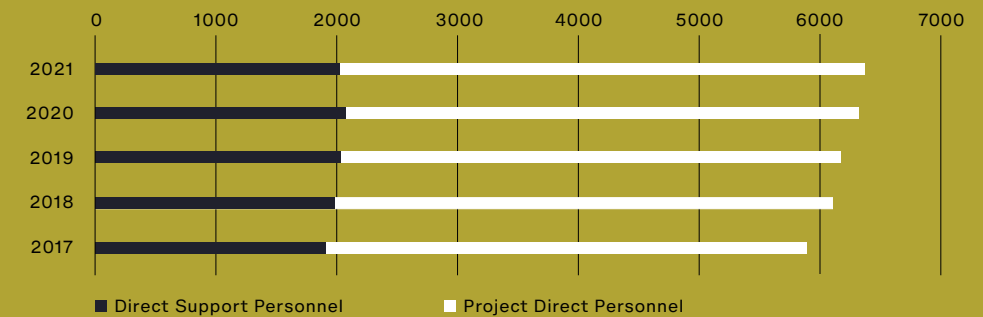
American Indian Sciences and Engineering Society 2021 Professional Award for Technical Excellence

# BUDGET & WORKFORCE

## 2021 BUDGET



## JPL PERSONNEL - FULL-TIME EQUIVALENTS



# LEADERSHIP

## CALTECH BOARD OF TRUSTEES JPL COMMITTEE

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### THOMAS F. ROSENBAUM

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Caltech

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Chairman Emeritus  
Intel Corporation

### GAYLE E. WILSON

Nonprofit Consultant

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**JONATHAN LUNINE** | Cornell University | Planetary Science

**BERRIEN MOORE** | University of Oklahoma | Global Environment

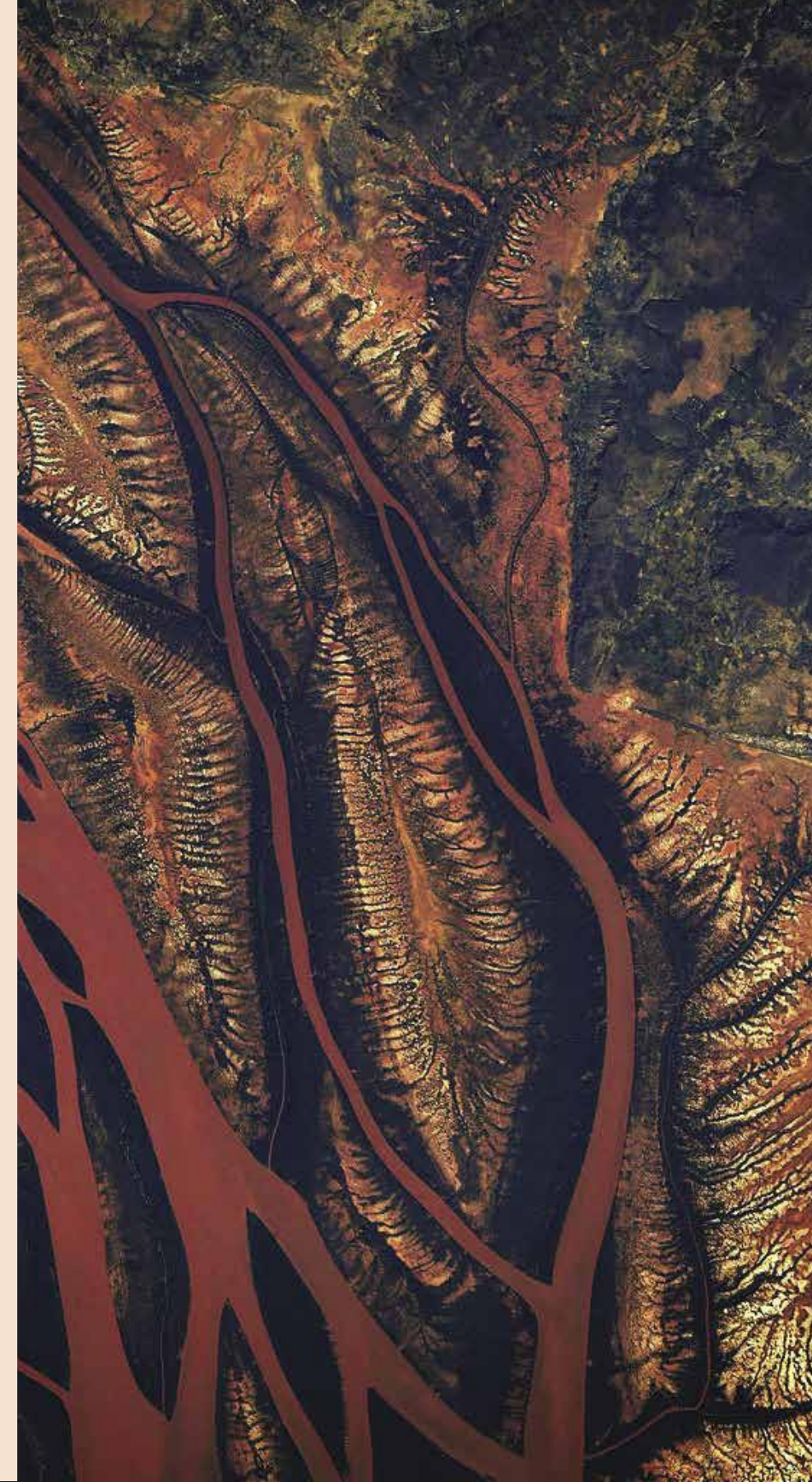
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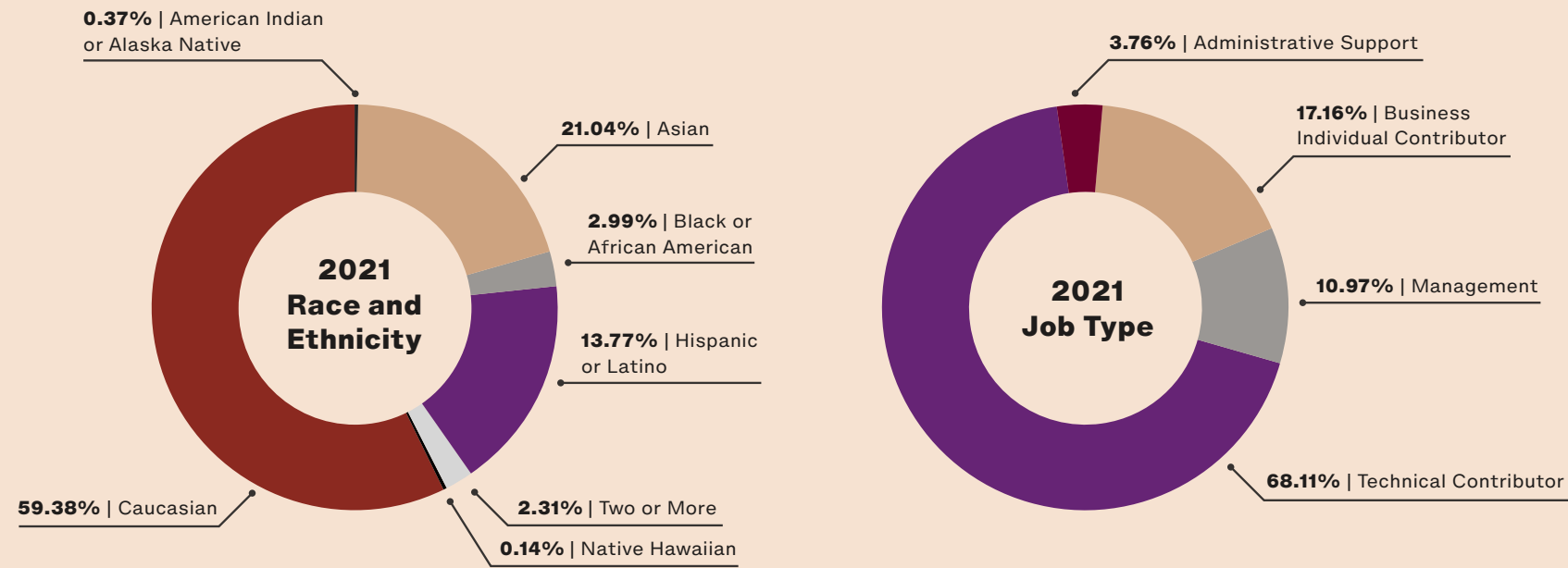
**ED WEILER** | NASA Associate Administrator (retired) | NASA Administration

**TOM YOUNG** | Lockheed Martin (retired) | Aerospace Management

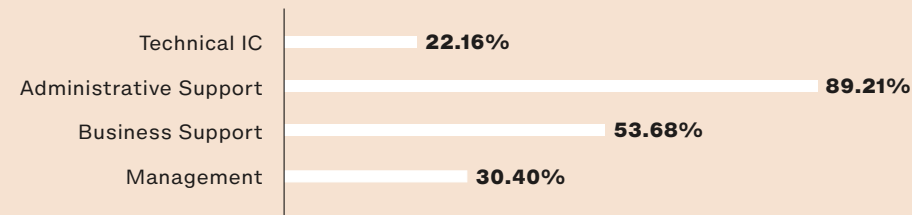




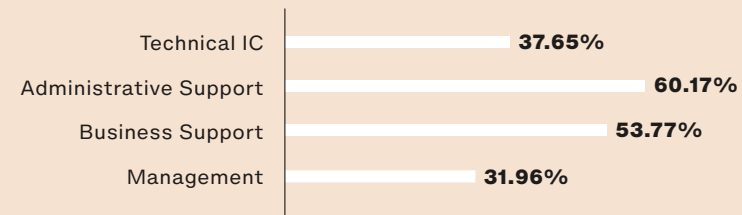
# WORKFORCE DEMOGRAPHICS



**% of Females in each Job Type**



**% of Minorities in each Job Type**



	FY21 Total Lab*	FY21 Technical Disciplines**
% of Females in the Population	30.99%	22.18%
% of Females Hired	40.76%	29.45%
% of Minorities in the Population	40.64%	36.78%
% of Minorities Hired	47.87%	43.84%

\*Population: The population in this data consists of JPL Employees in the Core Workforce (which excludes Students, Part Time, and Temporary workers) on Active or Paid Leave Status.

\*\*Technical: This population consists of JPL Employees in the Core Workforce whose assignment is in the following Job Families: Engineering, Institutional Leadership, LPPL, Research, and Software and Computing Systems.



DSN's Goldstone antenna lights up the night.

# EXECUTIVE COUNCIL

## **MICHAEL WATKINS**

Director (concluded August 2021)

## **LARRY D. JAMES**

Interim Director (effective August 2021)  
Deputy Director

## **DAVID GALLAGHER**

Associate Director,  
Strategic Integration

## **SAMMY KAYALI**

Chief Financial Officer, Manager of  
Operations Integration

## **LESLIE LIVESAY**

Associate Director,  
Flight Projects and Mission Success  
(effective March 2021)

## **RICHARD COOK**

Associate Director, Flight Projects and  
Mission Success  
(concluded March 2021)

## **BOBBY BRAUN**

Director for Planetary Science

## **SUZANNE DODD**

Director for Interplanetary Network

## **MARC GOETTEL**

Director for Business Operations

## **JIM GRAF**

Director for Earth Science and Technology

## **MICHAEL GREENE**

Director for Communications and Education

## **FRED HADAEGH**

Chief Technologist

## **COZETTE M. HART**

Director for Human Resources

## **RANDI LEVIN**

Chief Information Officer,  
Director for Information and  
Technology Solutions

## **JENNIFER LUM**

General Counsel, Caltech

## **PHILLIP MORTON**

Director for Safety and  
Mission Success (effective July 2021)

## **RICK NYBAKKEN**

Director for Safety and  
Mission Success (concluded July 2021)

## **KEYUR PATEL**

Director for Astronomy and Physics  
(effective April 2021)

## **MARK SIMONS**

Chief Scientist

## **CHARLES WHETSEL**

Director for Engineering and Science



Stag resting in the shade  
Credit: David B. Levine

