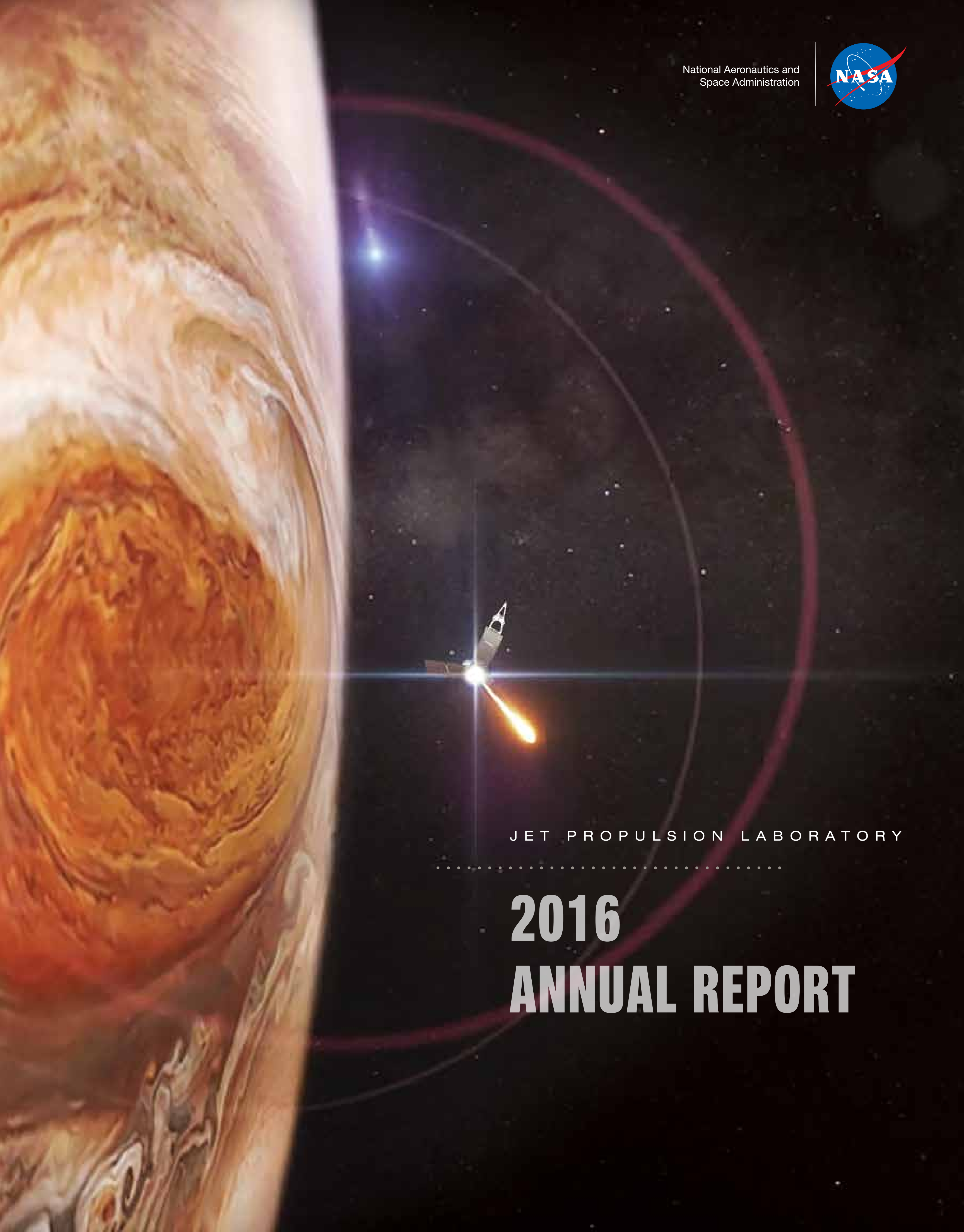
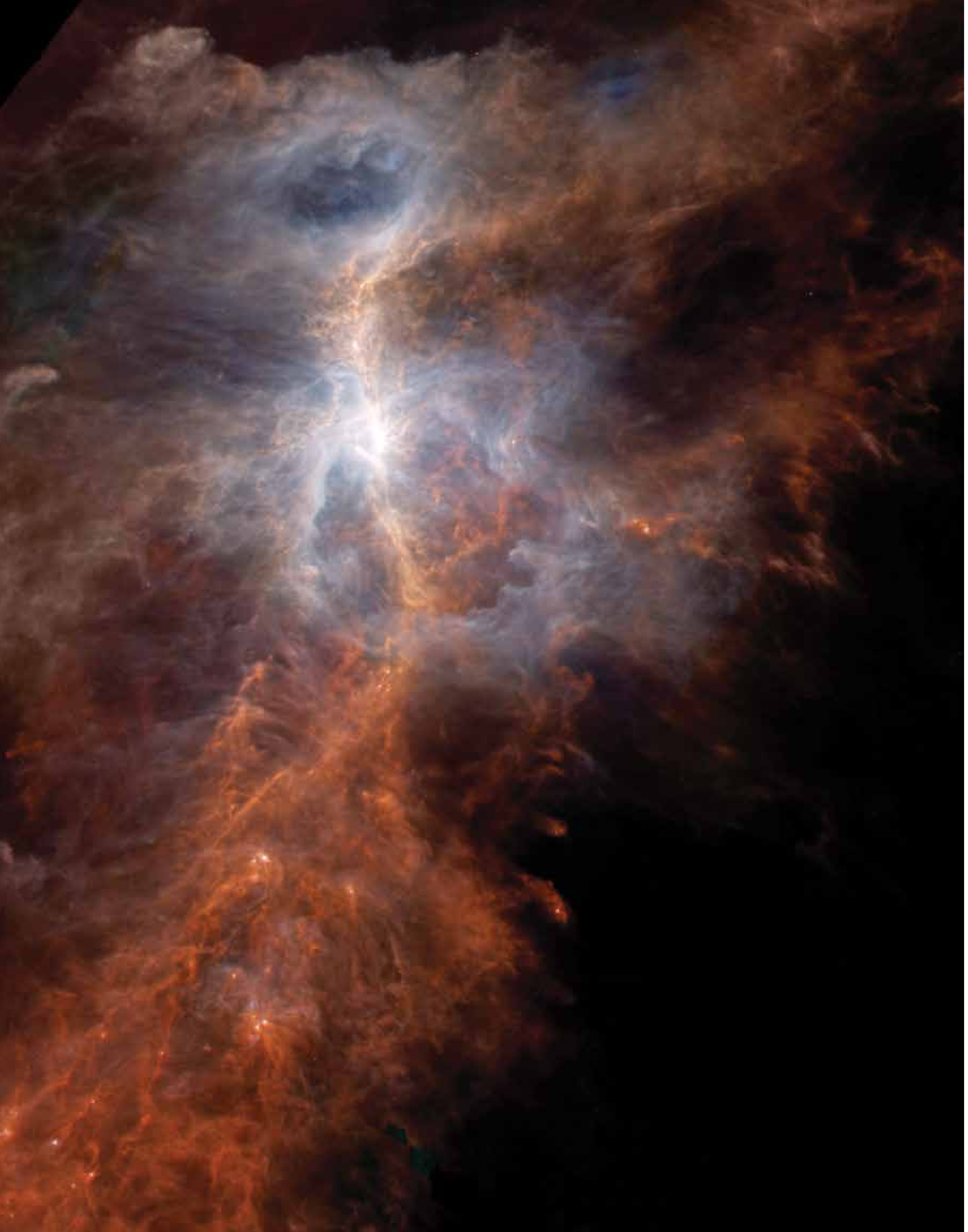


National Aeronautics and
Space Administration

JET PROPULSION LABORATORY

2016
ANNUAL REPORT



CONTENTS

COVER
An artistic impression of the Juno spacecraft's engine burn that placed it in orbit around Jupiter when it arrived July 4, 2016.

< The dusty side of the Sword of Orion illuminated in an infrared image released in 2016 from the European Space Agency's Herschel Space Observatory, for which JPL contributed key systems.

It was an honor to assume the role of JPL director halfway through 2016 — in fact, just days before the Juno spacecraft arrived in orbit around Jupiter on the Fourth of July. I look forward to continuing JPL's impressive legacy of exploration.

We anticipate that the intriguing data coming from Juno will help us learn more about how Jupiter, our largest planet, formed — a vital chapter in the story of our solar system. Work continues on the planned mission to Jupiter's icy moon Europa, believed to harbor a global subsurface ocean that might have the ingredients for life.

During its 12 years orbiting Saturn, the Cassini mission has revolutionized our knowledge of the ringed planet. The veteran spacecraft now heads toward its grand finale, in which it will repeatedly plunge through the narrow gap between Saturn and its rings. Because Cassini is running out of fuel, engineers designed this orbit to prepare for the mission's end in September, when it will dive into Saturn's atmosphere and send back data to the very end.

The Mars Curiosity rover explored the lower layers of Mount Sharp in 2016, investigating how ancient freshwater lake environments eventually became less hospitable for life. Curiosity and three other Mars missions — the Opportunity rover, the Odyssey orbiter and Mars Reconnaissance Orbiter — were extended. Preparations continue for the Mars 2020 rover and InSight, which will study the interior of Mars and how rocky planets form.

The Dawn mission continues exploring the dwarf planet Ceres, gathering detailed information about its origins, geology, composition and unusual features, including strikingly bright areas. Work has been continuing on a proposed asteroid retrieval mission, and JPL has now begun work on the Psyche mission to a metallic asteroid.

Monitoring Earth is always a priority for us. 2016 began with the successful launch of Jason 3, a U.S.–European oceanography satellite that continues a legacy of nearly 25 years of tracking global sea level rise. JPL deployed aircraft and researchers around the globe, including groundbreaking missions to study coral reef ecosystems, and the extent to which the oceans around Greenland are melting the edges of the ice sheet from below.

Beyond our solar system, the Kepler mission, whose development was managed by JPL, verified more than 1,300 planets in 2016. Work is progressing on future planet-hunting tools, such as starshade and coronagraph technologies.

Other technology breakthroughs include using augmented reality to bring Mars down to Earth for scientists, and artificial intelligence tools and other techniques to improve firefighter safety. Our big data experts renewed a partnership with the National Cancer Institute to benefit cancer researchers.

We are proud to explore our home planet, our solar system, and the far reaches of the universe through our connection with NASA and Caltech. We have an abundance of missions and projects, current and future, and I look forward to working with the exceptionally talented, hard-working men and women of JPL.

Dropping into orbit

SOLAR SYSTEM

They took a shot, and it could hardly have been more perfect. After looping around the solar system for five years — including a flyby of its home world, Earth — the Juno spacecraft celebrated the Fourth of July by dropping into orbit around the king of the planets, Jupiter. And it did that very precisely: The moment it came the closest to the giant gas planet was a mere one second off from the time designed by mission planners. >

A view of the sunlit part of Jupiter and its swirling atmosphere created by a citizen scientist, Alex Mai, using data from the Juno spacecraft's camera.

But this was to be no vacation in a serene locale. Nearly big enough to turn into a star, Jupiter is a hotbed of intense energy, harboring vast radiation belts like Earth's Van Allen Belts — only enormously stronger. Slipping over the planet's north pole and into an orbit taking it skimming just 2,600 miles above Jupiter's cloudtops was like a race for survival through a nuclear plant on meltdown.

For Juno's scientists, the risks are worth it. The solar-powered orbiter's close passes of the giant world offer a unique view of how the planet formed — and, in turn, how the solar system itself came to be. The mission also provides the opportunity to map Jupiter's gravity and magnetic fields, look for any evidence of a solid core, and track the auroras that dance near each of its poles.

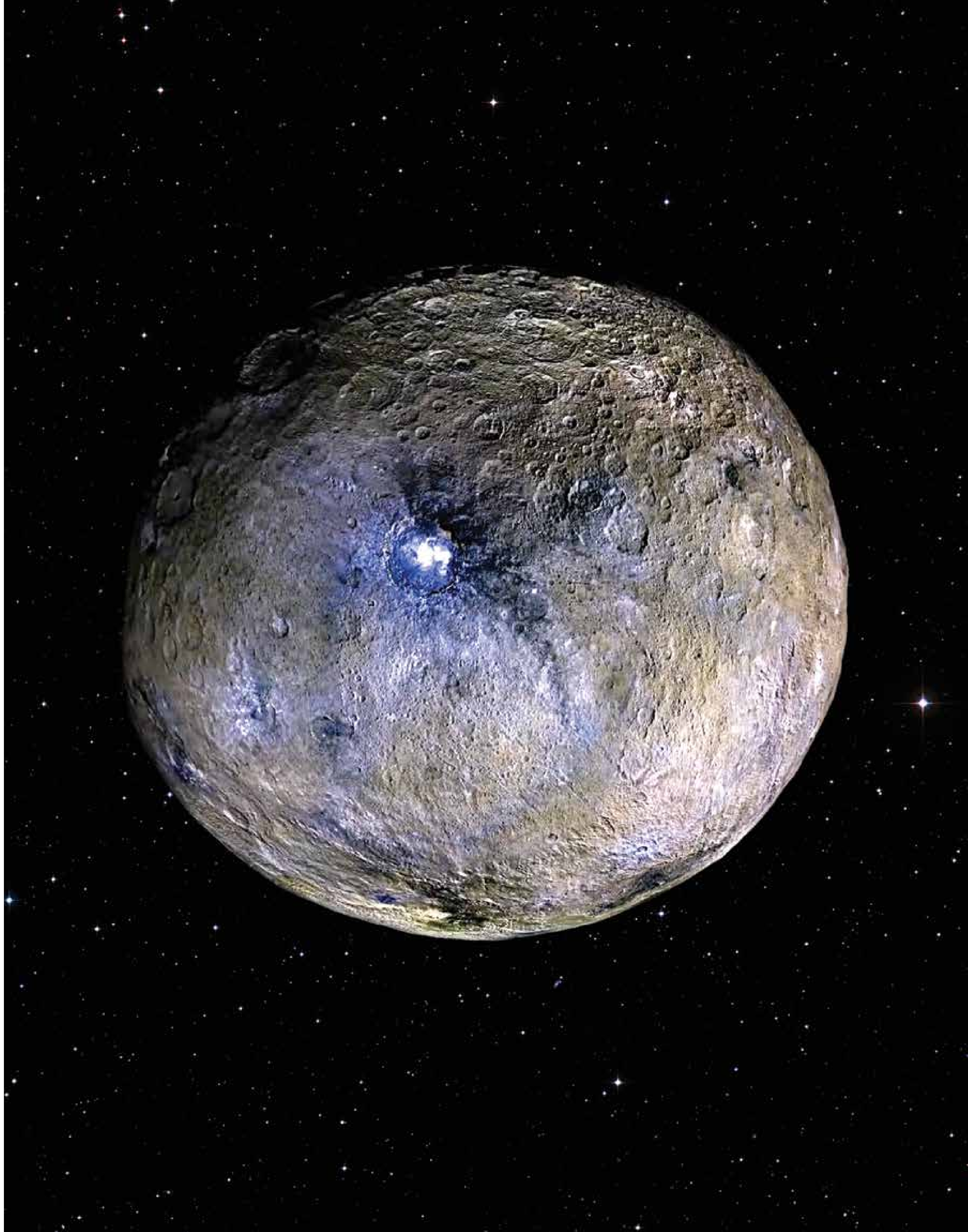
Juno's first few flybys of the planet gave the team plenty to reflect on. They were treated to the first-ever images of Jupiter's north pole — but there was no sign of any distinctive pattern, like the odd hexagon shape Cassini found at Saturn's north pole. Instead, Juno revealed storms including one cyclone described as a "towering beast of a storm" — more than half the size of Earth. Some storm features had an unexpectedly three-dimensional appearance.

Juno's arrival geometry put it into an orbit where it passes close to Jupiter once every 53 days. Plans originally called for the spacecraft to fire its main engine again to drop the time each orbit takes to only 14 days. Due to a pair of balky valves in the propulsion system, mission managers decided to hold off on the burn and leave Juno in its 53-day orbit at least through the end of the calendar year.

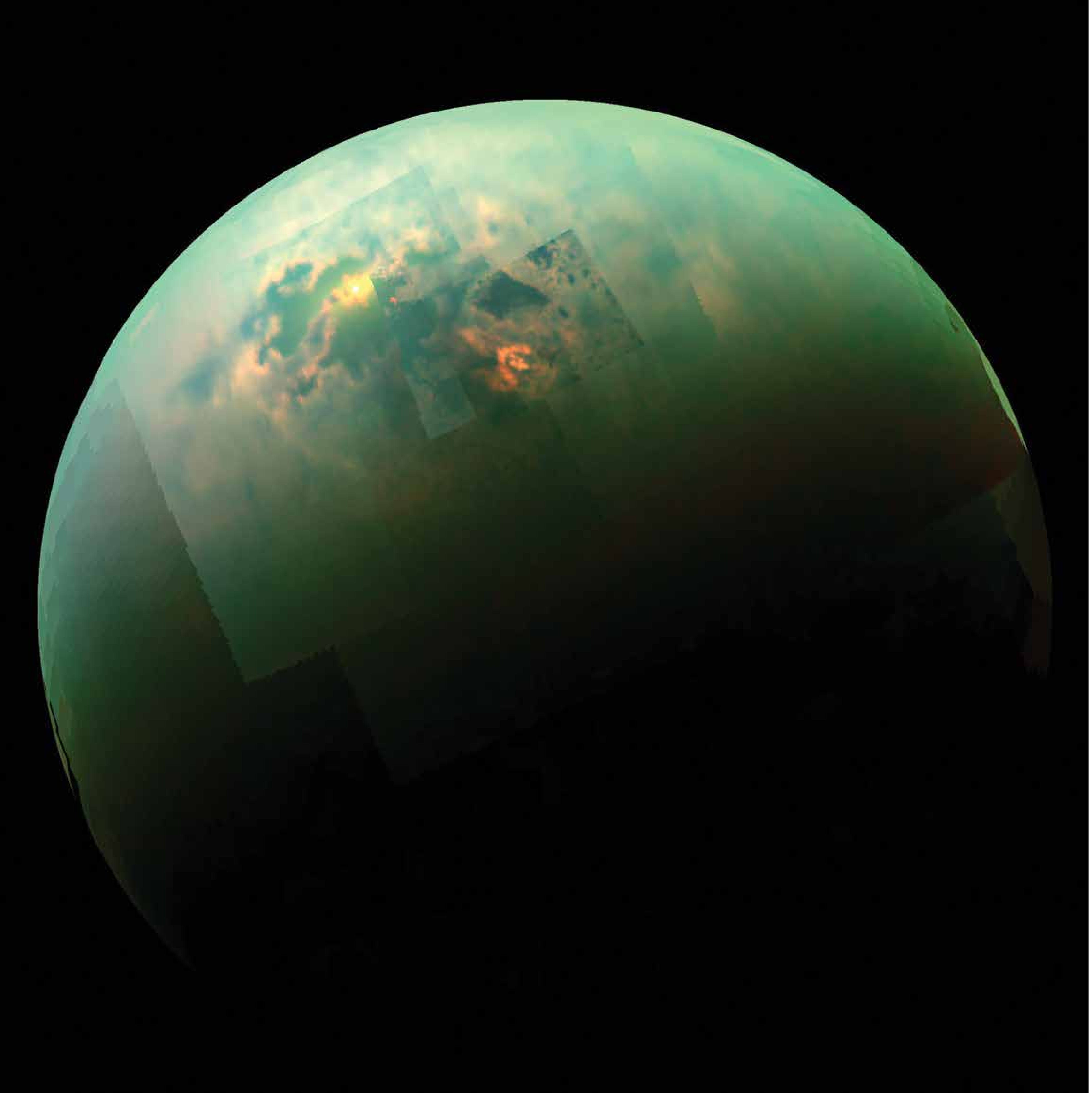
To probe Jupiter's interior, there was no need for Juno to carry a camera — but the mission team realized that being able to take pictures was a must for a mission to such a photogenic world. So the spacecraft carries JunoCam, an imager that will capture shots in a two-hour window as Juno races past Jupiter on each close encounter. In the spirit of citizen science, the public is invited to propose and vote on picture targets and review captured images on the mission's website.

DAWN • For the Dawn spacecraft orbiting Ceres, it's been bonus overtime. As 2016 began, the team hoped to eke out a few months in an exceptionally low-altitude orbit around the dwarf planet — lower than that of the International Space Station around Earth — before the hydrazine propellant for Dawn's thrusters was exhausted, spelling an immediate end to the mission. But the spacecraft proved exceptionally frugal in sipping the gas, meaning there was enough to keep going when the primary mission ended in June. NASA approved an extension through June 2017, and after another two months of low-altitude observations, the team instructed Dawn to spiral outward to a higher orbit where the spacecraft will be even thriftier with hydrazine, allowing it to perform new studies of the asteroid belt's largest object.

The picture of Ceres that has emerged from the Dawn mission is that of a dwarf planet loaded with water. Dawn spotted water ice at a number of locations, and much more must lie underground, even contributing to a cryovolcano that expelled a muddy mix of ice, rock and salt. Bright spots seen in many places on Ceres are likely salts remaining after briny water reached



> Occator Crater, home of the brightest area on the dwarf planet Ceres, stands out vividly in a mosaic of images captured by the Dawn spacecraft. Colors have been adjusted to bring out differences in surface materials.



the surface where water turned to vapor. But scientists still don't agree on where in the solar system Ceres formed. Given the mixture of chemicals Dawn found on Ceres, many think it must have taken shape beyond the orbit of Jupiter — or even as far out as the Kuiper Belt — and later brought closer to the sun through some gravitational pull of the planets. But others believe Ceres could have formed close to where it is now, and those chemicals were later brought to it by comets or some other means. Regardless of the verdict on Ceres, Dawn's time there and at the protoplanet Vesta proved ion propulsion's usefulness to hop from one solar system destination to another.

CASSINI • If Cassini were a TV show, 2016 would be the episode before the series finale. The grand conclusion, of course, will be in 2017, when the long-lived spacecraft caps its historic 13-year orbital tour by plunging into Saturn's atmosphere to vaporize itself, averting possible contamination of any of the ringed planet's moons. But there were plenty of memorable scenes for Cassini-watchers during the penultimate year.

Much of that excitement came at Titan, Saturn's largest moon and the only one in the solar system with a dense atmosphere and liquid lakes on its surface. In fact the chemistry on the organics-rich moon could be akin to the environment that led to life at Earth — but at deep freeze. For a second time, a study from Cassini data confirmed that a large sea on Titan is made mostly of pure liquid methane. Even the clouds that drift across Titan's skies are methane as well. In another observation, Cassini found deep steep-sided canyons on Titan flooded with liquid hydrocarbons — the first direct evidence of liquid-filled channels on the moon.

Saturn itself still retained new findings for the science team. Researchers "weighed" the planet's most massive ring for the first time, confirming that parts of the ring that are more opaque do not necessarily contain more material. And Cassini even extended its reach far beyond Saturn, when its cosmic dust analyzer identified a few specks of material originating far beyond the solar system in interstellar space.

But there's still that season finale to build the storyline for. In November, Cassini fired its thrusters to put it into "ring-grazing" orbits, some 20 once-a-week passes by the planet in which the spacecraft will fly high to the north before skimming past the outer edges of Saturn's main rings. Then in April 2017 Cassini shifts to its Grand Finale phase, passing as close as a thousand miles above the clouds as it dives repeatedly through the narrow gap between Saturn and its rings. That will climax in its mission-ending plunge into the planet's atmosphere in September 2017. Wistful though the team may be to see their spacecraft go, given that Cassini was running out of fuel, this plan offers the best opportunity to gather more compelling new science while protecting the ringed planet's

< Sunlight glints off the north polar seas of Saturn's largest moon, Titan, in a near-infrared image from the Cassini spacecraft.

Artist's rendering of the European Space Agency's Philae lander preparing to settle down on comet 67P/Churyumov–Gerasimenko as the Rosetta spacecraft carrying JPL's MIRO instrument orbits overhead.

moons from possible contamination. And then, as they say in Hollywood, "that's a wrap."

MIRO • As finales go, Europe's Rosetta comet mission — carrying JPL's MIRO science instrument — had a memorable one. After rendezvousing with comet 67P/Churyumov–Gerasimenko and sending a lander to the surface in 2014, the spacecraft spent two years in orbit as the comet banked around the sun. MIRO's job was to use microwaves to measure the temperature of the comet beneath its surface, and the amount of gas and dust given off as the comet heated up. That work done, European mission managers opted to go out on a high note by landing the spacecraft onto the comet nucleus in September 2016. An upside for scientists: the final descent gave all of Rosetta's instruments, including MIRO, views of the comet nucleus in unprecedented resolution — including a look into a large pit on the surface. But the work of the JPL instrument team was not finished; they continued work on delivering new data products to public archives.

EUROPA • One of the most significant new ventures to the outer planets continued to take shape as the Europa Mission made progress in its formulation phase. Planned for launch as early as 2022, the spacecraft will execute 45 flybys of Europa, a moon thought to harbor a vast subsurface ocean, during two years in orbit around Jupiter. NASA selected 10 science instruments to fly on the mission, including three to be built by JPL. The Lab also delivered a NASA-requested study looking at a possible Europa lander. Launched separately, the lander would meet up with the flyby orbiter and settle down on Europa using the same Sky Crane technology that delivered the Mars Curiosity rover.

ASTEROID REDIRECT ROBOTIC MISSION • The JPL-led project to snatch a multi-ton boulder off a near-Earth asteroid and move it into orbit around the moon picked up momentum when NASA gave the Lab the green light to proceed into preliminary design stage. The Asteroid Redirect Robotic Mission will demo a planetary defense concept by using ion propulsion to gradually deflect the boulder, placing it into a safe lunar orbit where it can be visited by astronauts as training for human missions to Mars. In 2016 the project issued a contract for advanced electric propulsion thrusters and worked with four aerospace companies interested in building the spacecraft, with launch planned in the 2020s.

Simulation of the Asteroid Redirect Robotic Mission spacecraft carrying off a boulder from a near-Earth asteroid to be placed in orbit around Earth's moon.

SENDING A CLEAR SIGNAL

Michela Muñoz Fernández can speak four languages, including Italian. That came in handy for NASA's Juno mission, which has two instruments developed by Italian scientists. Communicating effectively meant more than speaking in their native tongue — she also had to calm troubled waters roiled by cultural differences.

For seven years she strove to keep the teams talking, shuttling back and forth between JPL and Italy and holding teleconferences at the crack of dawn. She gave up all her free time to keep the flow of information steady and free of static because she knew what was at stake. "Mixed communications can lead to errors, and as we've learned with other space missions, minor errors can be catastrophic."

Due to the international nature of the collaboration she had to become well-versed in export restrictions, learning what she could share openly and what had to remain unsaid. She's justifiably proud that her efforts resulted in three successful instruments that are now gathering data as Juno orbits Jupiter.

Raised in Madrid, Spain, her childhood dream was to work for NASA. Visits to Cape Canaveral when she was a high school exchange student cemented that goal. The Deep Space Network, which talks with all spacecraft beyond the moon, fortuitously has a complex in Madrid. She worked for the company that manages the complex, and became entranced by space telecommunications and electrical engineering.

"I wanted to know, how does a machine transmit a message that comes from my mouth? I saw it as a fascinating puzzle, how different signals are propagated, how they become coded, depending on the shape of the antenna." She used that curiosity during her PhD studies at Caltech to design receivers that could capture weak signals emanating from other planets.

Her quest for coherent communication is comprehensive — from helping solve a relay problem for the Deep Space 1 mission, to easing interactions between different science teams. As the principal investigator on a machine-learning task for Mars Science Laboratory, she's even using artificial intelligence to catch tiny, imperceptible errors before they can escalate into a complete loss of signal.

A front-row view

EARTH

A quadcopter the size of a lawnmower hovers a few hundred feet over a volcano, equipped with an infrared camera to capture a thermal map of features below. Thousands of miles away, a remote-controlled aircraft flies over the eye of a sprawling hurricane, taking in a front-row view of the storm unlike anything possible from the ground or from space. Above the farming districts of California, the state's complex network of faults is the target for a radar instrument carried on a small plane. >

Coral reefs off Australia were the target of a major JPL expedition.

For JPL's Earth scientists, it's not all about satellites. For decades Lab researchers have also flown instruments closer to Earth on airplanes, and in recent years airborne campaigns have become a tool they turn to more frequently. Two-seater propeller planes, commercial-size jets, drones, balloons and blimps are all ways they are taking their instruments to the environments they need to study.

< Equipment is loaded onto a boat taking part in the Australian coral reef study.

V Artist's concept of the Jason 3 ocean satellite in orbit around Earth.

In 2016 one of those expeditions, the Coral Reef Airborne Laboratory, took aircraft to Hawaii and to Australia's Great Barrier Reef to check the health of those offshore environments. Flying 28,000 feet above the ocean, a new JPL imaging spectrometer carried by a twinjet aircraft collected data used to distinguish areas of coral, algae and sand. Combined with surface and undersea observations by divers, the campaign is designed to yield new scientific perspective on coral reefs — ecosystems that are not only beautiful, but also contribute an estimated $400 billion a year to the world economy as sources of food, medicine and tourist destinations.

Far to the north, in a vastly colder clime, researchers took part in a campaign called Oceans Melting Greenland designed to gauge how the ice fringe encircling the world's largest island is gradually being melted by the surrounding ocean. Using an imaging radar aboard a 10-seater jet plane, they spent weeks conducting a survey of Greenland's entire coast, examining zones of bedrock, glacier, icy freshwater and the warmer waters of the Atlantic. The five-year study will help scientists refine estimates of sea level rise in the decades to come.

Still other airborne campaigns deployed around the world during the year, examining air quality in Asia, clouds in the southern Atlantic and greenhouse gases in the United States. Not that such campaigns will replace Earth-orbiting satellites; each route to data-gathering has its strength. Satellites are unparalleled in delivering a global view, while airborne campaigns excel in flexibility and the high resolution of the data they collect. In 2016, those capabilities proved invaluable to the work of JPL's scientists.

JASON 3 • For more than a quarter century, JPL has teamed with France's space agency and other partners on a series of satellites devised to monitor global sea levels. In January 2016 that partnership bore new fruit when Jason 3 was launched from California. Like its predecessors, the newest Jason beams microwave pulses toward Earth to make precise measurements of the height of the world's seas. Collectively the Jasons (and their forerunner, called Topex/Poseidon) have verified that global sea levels rose an average of 2.8 inches since the early 1990s. Once in orbit, Jason 3 also eyed the

< A Gulfstream IV aircraft is readied to carry a JPL imaging spectrometer to assess the health of coral reef ecosystems off the coast of Australia.

Melting of glaciers at Greenland is the focus of a major JPL study.

ongoing El Niño warm-water anomaly in the eastern Pacific. With the Jason series now well-entrenched, NASA has passed the lead U.S. role to the National Oceanic and Atmospheric Administration, but the space agency and JPL retain key roles.

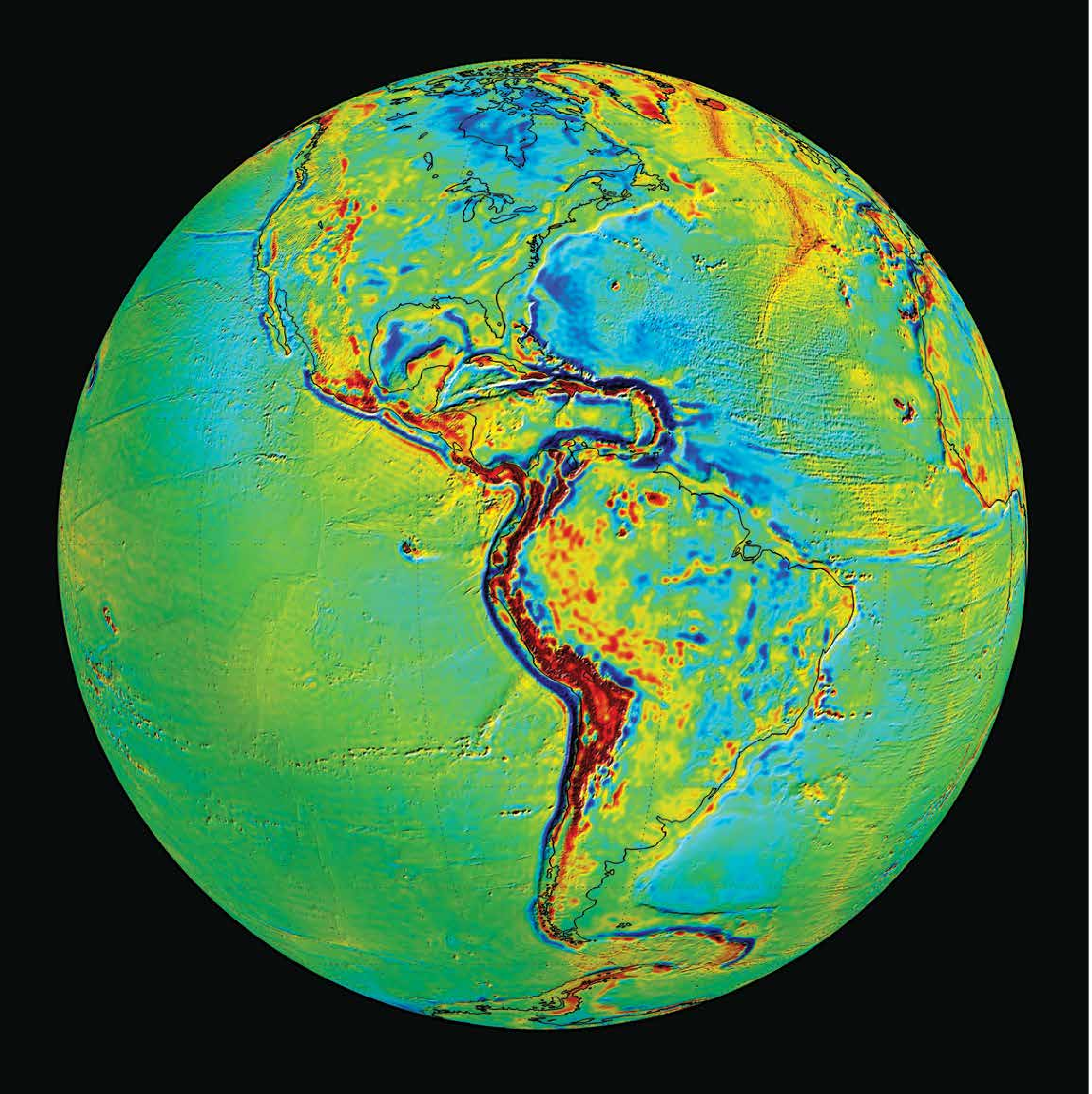
RAPIDSCAT • In 2014 RapidScat became the first Earth-observing instrument designed for permanent mounting on the International Space Station. Built quickly on a shoestring budget using spare parts, RapidScat spent two years in space monitoring ocean winds before concluding its mission in 2016. Those observations provided valuable data for weather and marine forecasting, tropical cyclone tracking and the study of phenomena such as El Niño.

UAVSAR • The shoreline in the Mississippi Delta region of Louisiana is notoriously unstable, but many areas became significantly more so following the Deepwater Horizon oil spill in 2010. JPL radar imaging is now helping authorities measure this change more accurately. The UAVSAR instrument aboard a twinjet plane made extensive overflights of the Delta to create maps of the area. They demonstrated that the shoreline was receding much faster in parts of coastal Louisiana affected by the oil spill.

In an unrelated study, JPL researchers used airborne radar to examine how New Orleans and its surrounding areas continue to sink due to both natural and human-induced processes. They found the highest rates of sinkage were upriver around major industrial areas and in New Orleans' Michoud district, where land is sinking by up to two inches per year. The causes? They are thought to be both natural geological processes and human activities such as groundwater pumping and the pumping of surface water to lower the water table.

OCO 2 • How are human activities contributing to greenhouse gases such as carbon dioxide in Earth's atmosphere? One answer was provided by Finnish scientists who created global maps using data from the Orbiting Carbon Observatory 2 mission. Some areas that stood out resulted from fossil fuel burning in Germany and Poland as well as in Kuwait and Iraq. Sub-Saharan Africa was another hotspot, though it is believed to be the result of fires.

NASA AIRBORNE • West Antarctica, scientists have known for years, is the site of some of the most serious glacier loss on the planet. New research is showing how that loss is taking place. One JPL-teamed study looked at how the melting of three west Antarctic glaciers is most intensive on their floating undersides. The one melting the fastest, Smith Glacier, is losing up to 230 feet in ice thickness each year — nearly six times the rate scientists previously estimated



for the region. The work was based in part on measurements of ice loss from the bottoms of glaciers using radar and laser altimeters flown in a NASA airborne campaign.

GRACE • It may not seem all that serious to hear that Earth's north pole wanders back and forth by as much as 37 feet, but even that amount of motion can play havoc with the accuracy of GPS systems. So scientists have good reason to keep close tabs on the wobble of the planet's spin axis. Using data from JPL's GRACE mission, they determined that one of the main causes for the drift is the movement of water around the globe. Around the year 2000, Earth's spin axis took a sharp turn to the east, which researchers attributed to loss of ice from Greenland and Antarctica. Another cause for the instability is the loss of water mass caused by depletion of aquifers and drought in India and the Caspian Sea area.

AIRBORNE SPECTROMETERS • Satellites have identified the Four Corners region where Utah, Colorado, Arizona and New Mexico meet as the single biggest source of methane emissions in the United States — producing one-tenth of all the methane released in the nation. Scientists believe the methane comes from natural gas extracted from coal beds in the area, which is home to more than 40,000 oil and gas wells. In a new study, two JPL airborne spectrometers collected data that shows only 10 percent of the region's individual methane sources are contributing half of the emissions. Those spots are putting out up to five and a half tons of the greenhouse gas every hour.

EARTH OBSERVING 1 • For the first time, an instrument on an orbiting spacecraft has measured the methane emissions from a single, specific leaking facility on Earth's surface. JPL scientists used a spectrometer on NASA's Earth Observing 1 satellite to view the accidental release of methane in Aliso Canyon, near Porter Ranch, California. The observation was viewed as an important breakthrough in the ability to eventually measure and monitor emissions of this potent greenhouse gas from space.

< South America's Andes mountain range stands out vividly in a display of gravity data combined from satellite altimetry, terrestrial measurements, and the GRACE mission.

THE WEIGHT OF WATER

The first time Felix Landerer sailed the oceans, he didn't set foot on land for a month. He was on a research vessel exploring the continental margin — the zone of the ocean floor that separates thin oceanic crust from thick continental crust — along the Pacific coast from Panama up to Canada.

That was the first of 15 sea voyages leading to a master's degree in geophysics. Wanting to continue his journey of discovery, he gravitated toward a PhD in physical oceanography. But instead of sailing the seas, he became immersed in an ocean of models and data.

Little did he realize these studies would eventually launch him into a space science career. The GRACE mission's twin satellites, orbiting Earth since 2002, take advantage of the same ocean models developed at the Max Planck Institute in Germany where he earned his doctorate.

GRACE detects minute fluctuations in Earth's gravity to see how mass — most of it water — fluctuates near Earth's surface. GRACE data keeps tabs on how glaciers are melting, how sea levels are rising, and even how water storage is changing in aquifers deep underground.

"GRACE essentially 'feels' mass changes through gravity, through tiny shifts of the two satellites' orbits," he says. "This gave us a whole new way of looking at Earth's water cycle that we never had before."

Landerer is the deputy project scientist for the upcoming GRACE Follow-On mission. He and others are also now dreaming of future versions. One possibility is to miniaturize the current instruments, with a constellation of CubeSats in orbit around Earth: human-made stars keeping tabs on the many changes below.

As a child he loved to take things apart to learn how they worked, and the innovation of GRACE to measure the weight of our watery world inspires him. "I find it amazing that two boxes orbiting 400 kilometers above us can detect mass variations at the bottom of the sea."

Search for other worlds

ASTRONOMY & PHYSICS

In the hunt for planets orbiting other stars, the numbers keep mounting up. By the end of 2016, more than 3,200 exoplanets had been verified, some 2,325 of them discovered by the Kepler space telescope. In May 2016 alone, the Kepler team announced that 1,284 new planets had been verified, 550 of which were the right size to be rocky planets; of those, nine orbit in their star's habitable zone. >

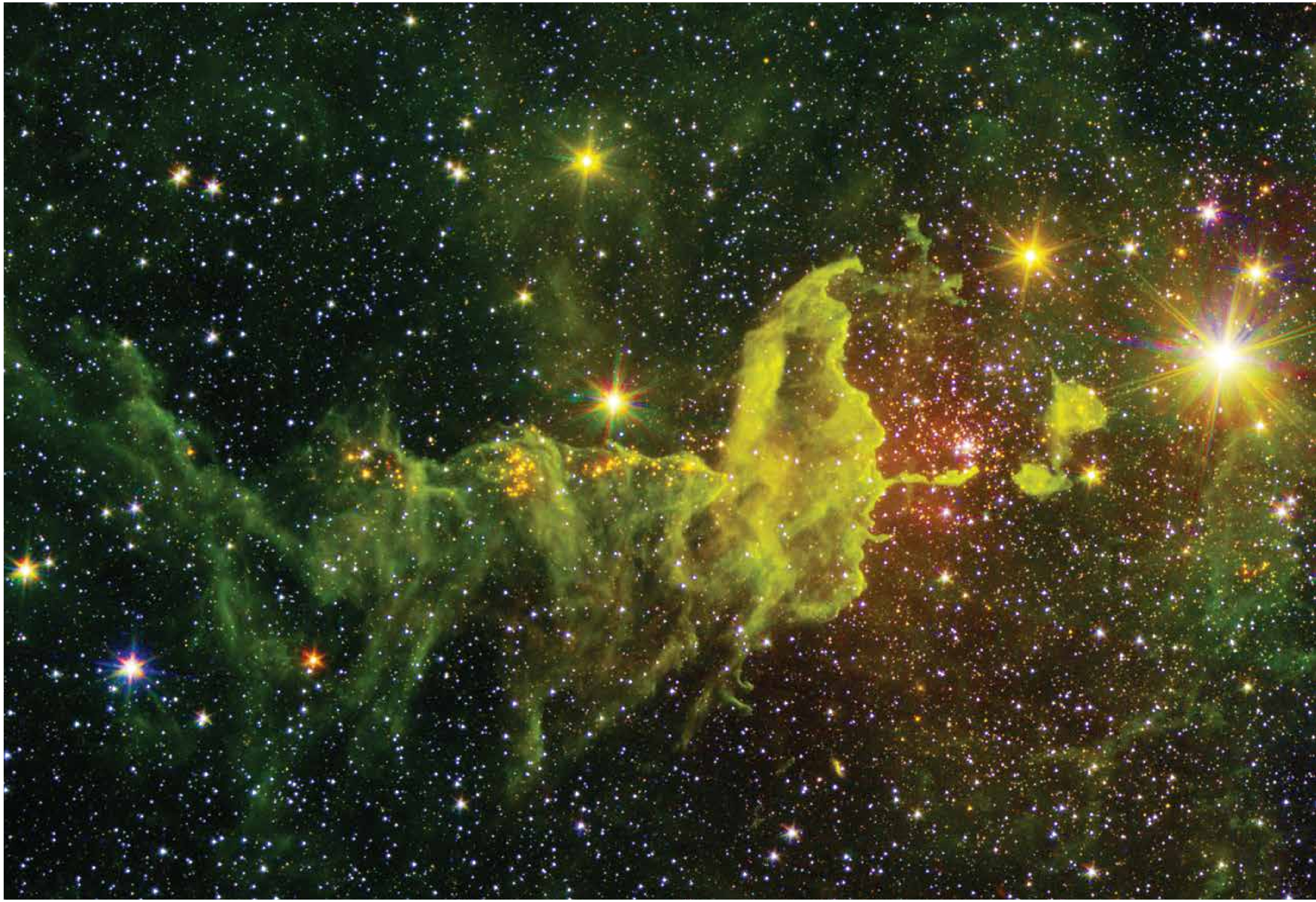
A study of a protoplanetary disc surrounding another star (depicted here in an artist's illustration) using data from the Spitzer Space Telescope and ground telescopes could help astronomers understand how exoplanets form.

The challenge now for those seeking these worlds is to take their search to a new level. What technologies will enable future space telescopes to see exoplanets and search for evidence of possible life? The biggest challenge in observing such planets is to combat the enormous glare from their parent stars. So to see the planets, astronomers need to suppress the starlight — essentially, to create a miniature solar eclipse.

Two technologies are being pursued to do that. One, a coronagraph, places a mask in the path of light inside a spaceborne telescope to block starlight, allowing the fainter glow of planets to pass through. The other, called starshades, blocks starlight with larger shades placed outside the space telescope. JPL is very active on both fronts.

The Lab is preparing to build an advanced coronagraph to fly aboard NASA's Wide-Field Infrared Survey Telescope, planned for launch in the mid-2020s. That coronagraph should be able to directly image and observe exoplanets as small as Neptune around the nearest stars, and to prove the technology needed for a next mission that will find Earths around other stars. In 2016, JPL ground tests demonstrated coronagraph performance capable of detecting Jupiter-size exoplanets around nearby stars.

On the starshade front, in 2016 JPL was asked to lead a technology development activity to mature all of the engineering needed to make such systems work in space. Working with outside companies, JPL developed a prototype starshade design with flower-like petals folded like origami to pack the system



> The spider portion of a nebula called the Spider and the Fly, seen in an infrared image combining data from the Spitzer Space Telescope and the Two Micron All Sky Survey.

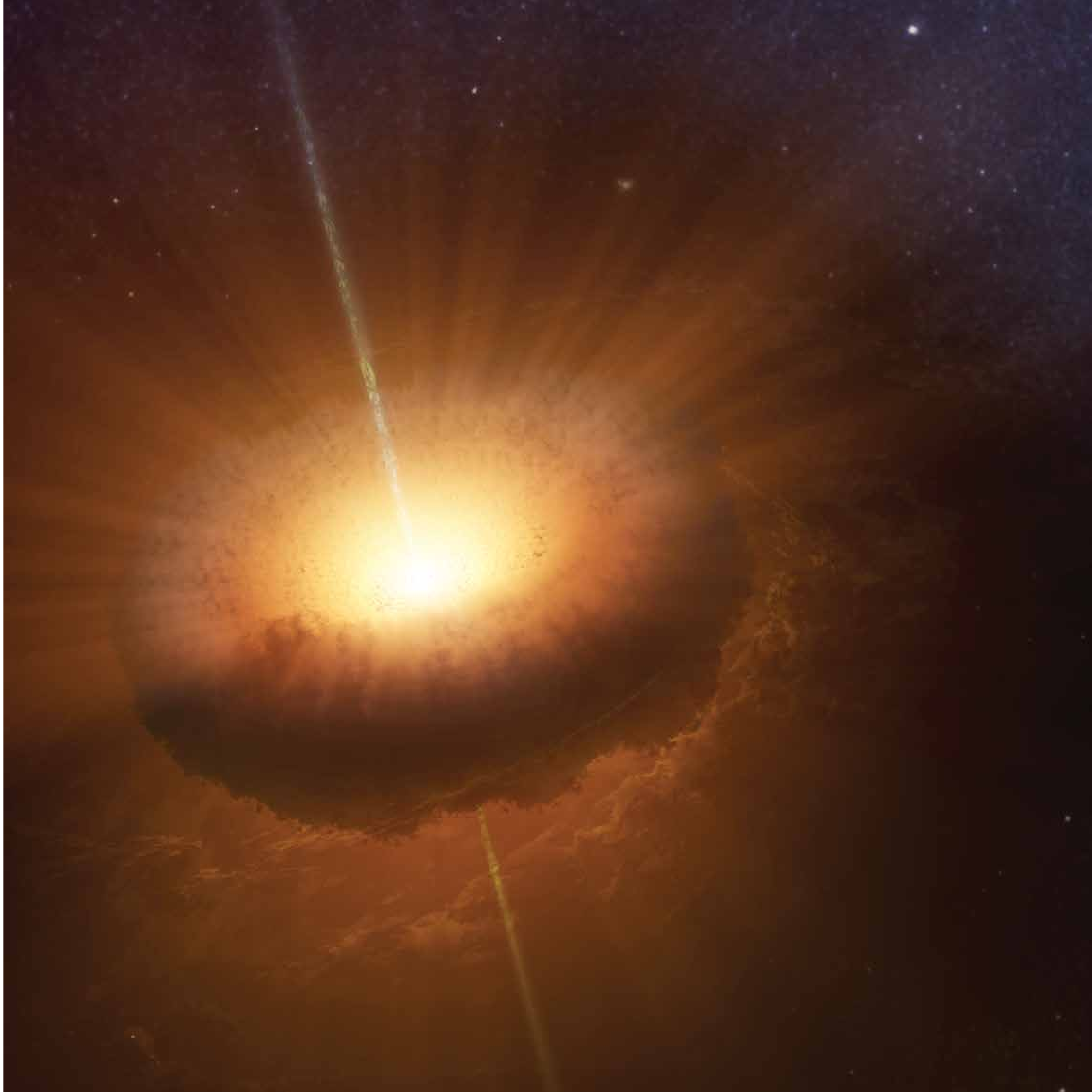
for launch. In the next decade, those efforts should lead to ever more powerful instruments in space enabling us to possibly find worlds like our own.

∧ Blue dots mark galaxies that contain supermassive black holes emitting high-energy X-rays — just a few of hundreds of such galaxies observed by NuSTAR.

SPITZER SPACE TELESCOPE • Thirteen years after launch and its infrared coolant long-ago boiled away, the Spitzer Space Telescope still remains remarkably productive. Observations with Spitzer led to the first temperature map of a super-Earth planet — a rocky planet nearly two times as big as ours. The map reveals extreme temperature swings from one side of the planet to the other, and hints that a possible reason for this is the presence of lava flows.

NUSTAR • Supermassive black holes in the universe are like a raucous choir singing in the language of X-rays. When black holes pull in surrounding matter, they let out powerful X-ray bursts. This song of X-rays, coming from a chorus of millions of black holes, fills the entire sky — a phenomenon astronomers call the cosmic X-ray background. New data from the Nuclear Spectroscopic Telescope Array, or NuSTAR, have, for the first time, begun to pinpoint large numbers of the black holes belting out the highest-energy X-rays.

WISE • In a far-off galaxy 12.4 billion light-years from Earth, a ravenous black hole is devouring galactic grub. Its feeding frenzy produces so much energy that it stirs up gas across its entire galaxy. Called W2246-0526, it is the most luminous galaxy known, according to research based on data from the Wide-field Infrared Survey Explorer. That means that it has the highest power output of any galaxy in the universe, and would appear to shine the brightest if all galaxies were at the same distance from us.



> Artist's concept of an unusual celestial object called CX330, determined to be the most isolated young star ever discovered, based on data from the Wide-field Infrared Survey Explorer and Spitzer Space Telescope.

A HEAD IN THE CLOUDS

Anita Sengupta embraces engineering extremes, from the design of a probe for scorching-hot Venus, to Mars parachutes that deploy at twice the speed of sound, to experiments that will travel 17,150 mph in free-fall around Earth, onboard the International Space Station.

The Cold Atom Laboratory not only will be moving fast, it will be the coldest spot in the universe. The instrument, which won Popular Mechanic's Breakthrough award for 2016, will use lasers to push against atoms to slow them down.

"At these incredibly cold temperatures, atoms do something unusual — they move together in unison, like a wave," she says. "This can give us insight into the quantum realm and explain strange properties, like superfluidity and superconductivity."

Known as Bose–Einstein condensates, these clouds of atoms have been made in labs on Earth where they're affected by the pull of gravity. In the space station's microgravity, the cloud of atoms can be made much colder — a billion times chillier than the vacuum of space. Microgravity also will allow the atom clouds to persist longer. "On the ground we can only observe them for milliseconds before they fall out of the trap, due to the pull of gravity."

After it launches in 2017, this "cloud in a box" experiment will be highly sensitive to all kinds of fields, including gravity and Earth's magnetic field. The instrument could help us better understand the nature of dark matter, gravity, and how complexity arises in the universe.

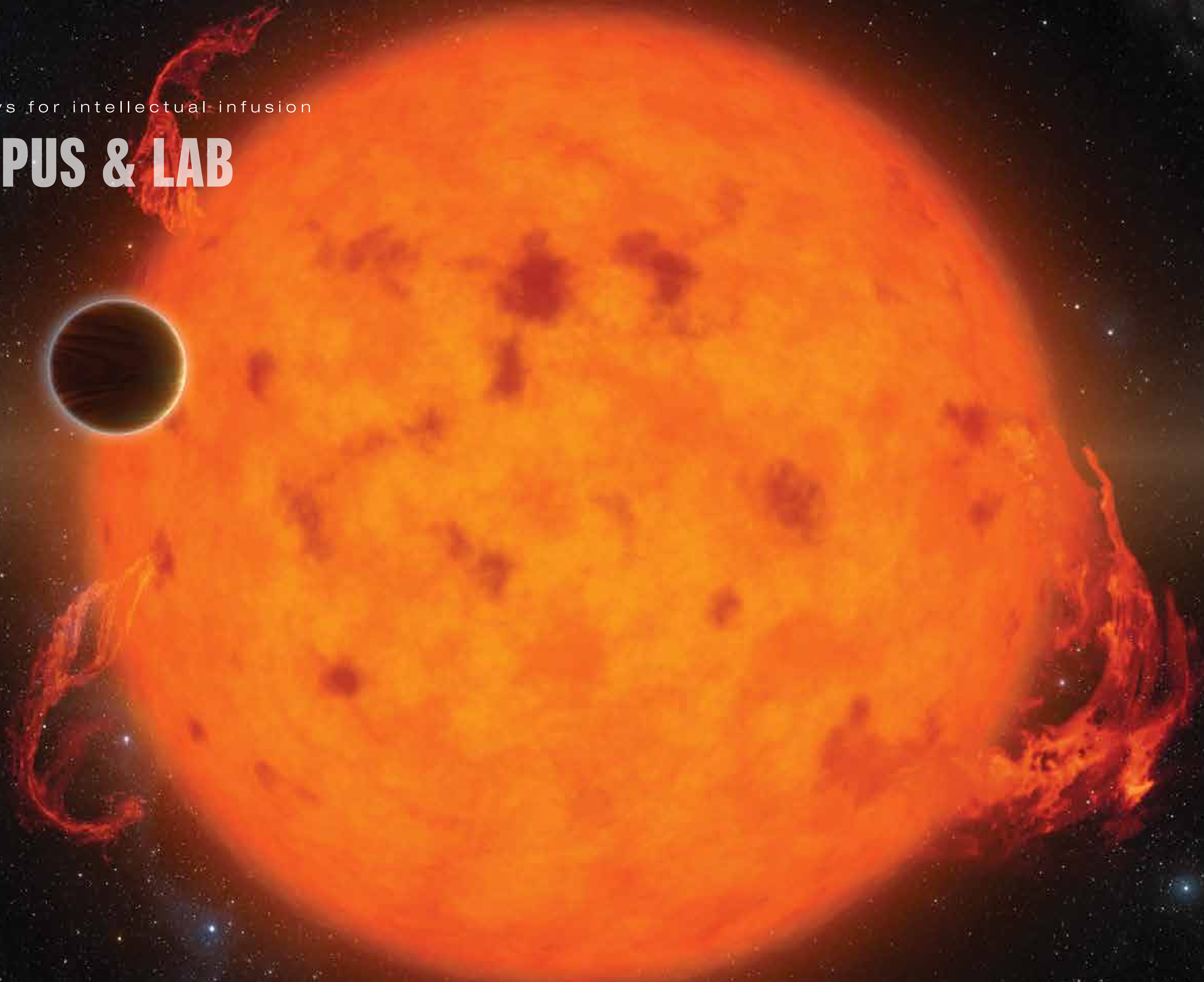
In the realm between caution and risk, Sengupta finds her balance. She loves to ride motorcycles through mountain canyons, but these days she's more often zooming through the skies in a Cessna Skyhawk. Practicing for her pilot's instrument rating, she says, is one of the toughest challenges she's ever faced. "Flying in the clouds, you don't have any visual cues. You have to rely on the instruments, which can contradict what you're feeling, and you have to overcome that."

PROFILE

ANITA SENGUPTA

Pathways for intellectual infusion

CAMPUS & LAB



JPL continues to benefit from its special identity as a NASA laboratory that is also part of one of the world's great research universities. Numerous collaborations, joint appointments and other initiatives offer pathways for intellectual infusion that enrich JPL's missions and scientific efforts. >

New optical systems to study exoplanets is one of many collaborations between JPL researchers and Caltech campus faculty.

COLLABORATIONS • Many collaborations are born at the Keck Institute for Space Studies, a joint Campus–Lab think tank. Since it was created eight years ago, more than four dozen science and technology investigations teaming campus faculty with JPL and external researchers have been completed. Initiatives active in 2016 included a study of how optical data transfer can relieve the communication bottleneck currently experienced by small spacecraft; an exploration of the next generation of optical systems for characterizing exoplanets; strategies for producing oxygen and rocket fuel on Mars using sunlight, and a critical evaluation of the use of advanced robotic systems as surrogates for human explorers on the surfaces of planets and moons. The institute's initiatives are highly interdisciplinary — teaming scientists from many specialties with instrument-builders and other technologists.

RESEARCH • Campus–Lab synergy has also been boosted by the President's and Director's Fund, a program founded three years ago to support research teaming Caltech and JPL investigators. The 2016 research included studies of trends in Antarctic sea ice, the use of radio pulsars to probe the center of our galaxy, and spaceborne mapping of hazards and property damage in ground on Earth that loosens, or "liquefies," due to earthquakes or other stresses.

MISSIONS • In all, 12 JPL missions benefit from campus participation. The project scientist for JPL's Mars 2020 rover mission is a member of the Caltech faculty, and NuSTAR is led by a Caltech principal investigator. More than 109 JPL staff serve as lecturers or associates at Caltech. Ten Caltech faculty have joint appointments at JPL.

> Trends in Antarctic sea ice is among the topics of initiatives enabled by the President's and Director's Fund.

Prospecting on the Red Planet

MARS

For the storied Curiosity rover, the message of 2016 was clear: the road is getting steeper. But then again, the team guiding the robotic geologist always knew that it would. Since its landing in 2012, the ultimate prize was to be Mount Sharp: an 18,000-foot mound of sediments at the center of Gale Crater. In its first years on Mars, Curiosity uncovered evidence of ancient rivers and lakes, and all the necessary ingredients for life. Now, two years after arriving at Mount Sharp's base, the rover would push further to find what its higher elevations held. >

Self-portrait of the Curiosity rover at a drilling location nicknamed Quela in the Murray Buttes area on lower Mount Sharp on Mars.

A panorama of Murray Buttes showing the turret of tools on Curiosity's robotic arm in the foreground, in an image processed by public enthusiast James Sorenson.

But first, there were stops along the way. As 2016 began, Curiosity was wrapping up a study at a sprawling field of sand dunes, the first to be viewed close up on any planet outside Earth. To proceed farther, the rover had to maneuver around the dunes and travel through a scenic landscape of isolated sandstone towers called Murray Buttes that are reminiscent of Monument Valley in Arizona and Utah. The buttes are named in honor of the late Caltech scientist and former JPL director Bruce Murray.

As it rolled forward, Curiosity was also climbing. In 2016 the rover moved upward about 260 feet, roughly equaling the elevation gain it had achieved previously in the entire mission. The stuff the rover was now rolling over was mudstone, fine-grained sedimentary rock built up over millions of years since Mount Sharp began to form. The mission's scientists concluded it was likely lake deposits — not necessarily from a single lake that filled all of Gale Crater, but perhaps shallow lakes that once dotted around the landscape.

By year's end, Curiosity had driven more than nine miles since landing in 2012. Ahead are another four miles or so to go to reach minerals mission scientists are eager to sample. Getting there will require an uphill climb of another 1,300 feet. While the going is getting steeper, the science discoveries could be even better in the days ahead.

OPPORTUNITY • Opportunity just keeps going and going — and going. As 2016 closed, the solar-powered rover with an original 90-day warranty had spent nearly 13 years prospecting in Meridiani Planum, a vast plain on Mars' equator, in the process racking up 27 miles of driving. For the past five of those years it has explored the western rim of Endeavour Crater, a 14-mile-diameter bowl scooped out when an ancient space rock hit the planet. The rover spent much of 2016 in Marathon Valley, a rift running from the rim down into the crater. At one point it appeared that that might be the mission's final act, but in mid-2016 NASA approved a two-year extension. That will allow Opportunity to reach and drive down into a valley that could have been formed by water. That will take it for the first time into the interior of Endeavour Crater. On its way to Marathon Valley, Opportunity caught sight of a crater given the name Spirit of St. Louis, an odd elliptical depression with a distinctive spire at its center.

MRO • Not for nothing has Mars long been called the Death Planet — and a reminder of why was experienced by NASA's colleagues at the European Space Agency, who in October witnessed the arrival of their Schiaparelli experimental lander not far from the area being explored by the Opportunity rover. A minute before touchdown, the European lander's signal was lost. Diagnostic help came from the cameras on Mars Reconnaissance Orbiter, which imaged apparent impact sites of the lander, its parachute and heat shield. Meanwhile, Europe's ExoMars Trace Gas Orbiter, which had launched alongside the lander, successfully dropped into orbit around the Red Planet. That orbiter carries a pair of radios provided by NASA/JPL, called Electra, to act as a relay for communications with rovers and landers on the Martian surface — another example of NASA's and JPL's commitment to international partnerships.

MARS ODYSSEY • In the realm of longevity records, Mars Odyssey achieved one of its own: in 2016 this spacecraft clocked 15 years orbiting the Red Planet. One of Odyssey's most critical contributions is as a relay for communications with the Curiosity and Opportunity rovers. But it continues to deliver science as well. Using Odyssey's thermal emission imager, scientists announced that seasonal dark streaks on Mars suspected to be caused by water running downhill are in fact as dry as the driest desert sands on Earth.

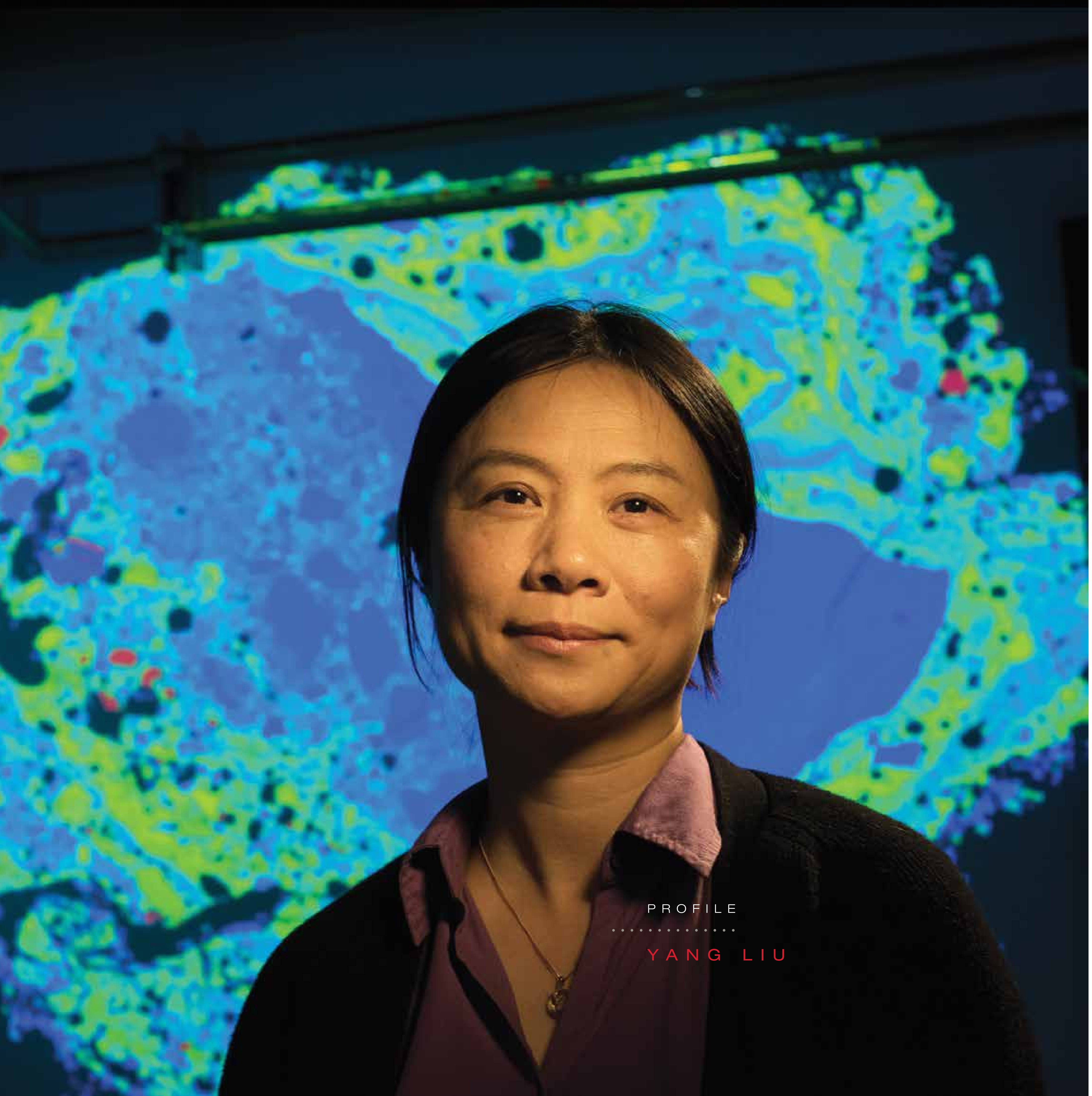
MARS 2020 • For JPL's next rover, Mars 2020, the big picture is the easy part: it is being broadly modeled on the Curiosity rover that has been rolling across the Red Planet since 2012. But beyond that, the devil is in the details — and for the new rover, there are many. Like its predecessor, the 2020 rover will probe Martian rocks for evidence of past life, but it will do so with new instruments — and will also cache rock and soil for a possible future sample return mission. In addition, creating the new rover in many ways amounts to a do-over allowing engineers to upgrade areas that posed challenges for Curiosity — such as beefing up the rover's aluminum wheels to ruggedize them for road trips across sharp rocks.

In 2016, NASA formally signed off on JPL's preliminary design of the 2020 rover. That doesn't mean, however, that building the rover only then got underway; it inherits so much from Curiosity that the project team has been procuring and fabricating hardware for several years. Scientists and engineers, meanwhile, narrowed down the list of possible landing sites to eight, and expect to pare that down to four finalists in early 2017. Thanks to advanced capabilities of the automated navigation that will guide the spacecraft's descent and landing, planners are able to consider intriguing locales that previously would have been judged too risky. Overall the project is on track for a summer 2020 launch, with landing in February 2021.

INSIGHT • It's official: Spring 2018 will be the launch period for the InSight mission to study the deep interior of Mars. Originally targeted for 2016, the launch was slipped to allow time to resolve a vacuum leak in its prime science instrument, designed to measure ground movements as small as half the radius of a hydrogen atom. Scientists expect InSight to help them understand how rocky planets like Mars or Earth formed and evolved.

< JPL's Electra radio, which has flown on American and European orbiters at Mars.

> Engineers and technicians at Lockheed Martin Space Systems test deployment of the solar arrays on the JPL-managed InSight lander.



STORIES IN STONE

The first mineral Yang Liu ever saw was a block of calcite, starkly white and geometrical. She found it one summer while running around the geological survey compound where her father worked and her family lived in China.

The calcite had been lying on the ground, thrown away as rubbish, but its inherent beauty spoke to her. Liu has been paying close attention to rocks and minerals ever since, extracting value from what most people would discard as unremarkable.

One such rock entered Earth's atmosphere as a fireball and exploded in the air above Tissint, Morocco, spreading its fragments far and wide. Liu has a small piece of that meteorite. Black on the outside and gray inside, it looks like an ordinary meteorite, but a closer look reveals it's extraordinary. For one thing, its composition proves this rock came from Mars. Liu and her colleagues also discovered two new minerals within the Martian rock, and named one "tissintite."

Liu has been investigating water and rock interactions since her graduate studies at the University of Michigan, where she grew bubbles in volcanic glass to see how water and carbon dioxide power the explosive eruption, "like bubbles in a glass of champagne." She then chased evasive water in lunar soil and minerals, and in Martian impact glasses. Her experience has been useful in developing the PIXL instrument for the Mars 2020 mission.

PIXL will comprehend rocks better than previous X-ray instruments sent to Mars. Not only will it provide pinpoint analysis of the mineral composition, targeting an area as small as a grain of salt, but it also will consider texture — which can say a lot about a rock's origin and history.

"My dad often said, 'Think twice before you speak,'" says Liu. She often had that phrase in mind as she struggled to communicate when she arrived in America as a graduate student. That idea also could be applied to her studies in stone, where a first glance is just the first step toward discovering deeper stories held within.

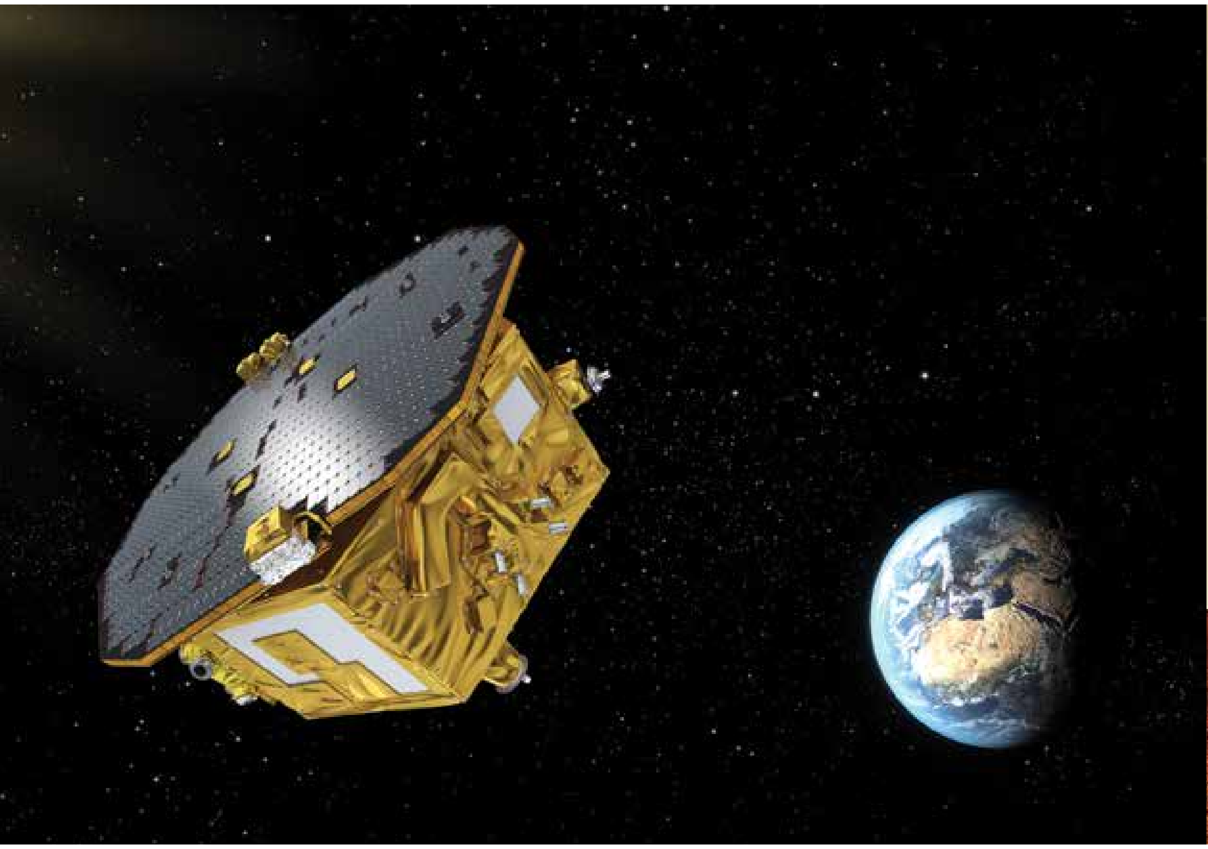
Things that have never been done

TECHNOLOGY

Pushing the boundary is at the heart of JPL's work. The Laboratory exists precisely to find ways to accomplish what has never been done. And to do that, JPL has a steady appetite for new technologies.

Technology development in fact is very prominent across the JPL org chart. Much of this work is focused on mission-enabling technology for space exploration projects. Other efforts support JPL's work for non-NASA federal sponsors such as the Department of Defense. And yet other technology work is born from JPL's work with commercial partners. >

A JPL materials engineer holds an advanced thermoelectric converter that could be used in future higher-performance space power systems.



JPL technology designed to hold a spacecraft's position still with extremely high precision is flying on the European Space Agency's LISA Pathfinder mission.

Center image: Concept for a helicopter that could fly on future Mars rovers.

One technology initiative that has already captured the public imagination is the Mars Helicopter. A small rotor-powered vehicle first conceived for Mars exploration, in theory versions of the helicopter could venture as well to other bodies with atmospheres, such as Saturn's moon Titan. JPL created one prototype helicopter and successfully tested it in the Lab's 25-foot test chamber that can simulate the atmosphere of Mars. It is under consideration to fly as a technology demonstration on the Mars 2020 rover or another future mission to the Martian surface.

SPACE TECHNOLOGY 7 • An advanced system of thrusters designed by JPL could pave the way for future missions such as gravitational-wave hunters that require extremely stable platforms in space. The system, called Space Technology 7, has been flying on a European spacecraft, LISA Pathfinder, which is testing technologies for a future space-based gravitational-wave observatory. The JPL system can hold the spacecraft's position completely still to within 2 nanometers — about the diameter of a DNA helix.

VARIED SPONSORS • Many JPL instruments and satellites are created for sponsors other than NASA. Among projects recently completed, the Compact Ocean Wind Vector Radiometer will monitor sea state for the National Oceanic and Atmospheric Administration (NOAA) and the U. S. military. The Defense Advanced Research Projects Agency engaged JPL to build two CubeSat instruments for high-frequency analysis. On behalf of the Air Force and NOAA, JPL completed six satellites called COSMIC 2A that will use GPS radio occultation measurements to improve weather forecasting. Another project planned for launch in 2017, called Deep Space Experiment, will carry aloft a 50-meter (164-foot) boom.

AUDREY • Artificial intelligence may not have helped the space crew in Hollywood's "2001: A Space Odyssey," but it's a boon to firefighters on Earth. A JPL-developed system called AUDREY is designed to collect data on temperatures, gases and other danger signals and guide a team of first responders safely through the flames.

HOLOLENS • And virtual reality took a major step forward with a JPL collaboration with Microsoft on a system called the HoloLens. Users don a headset to experience what is dubbed "mixed reality," where virtual elements are merged with the user's actual environment, creating a world in which real and virtual objects can interact. "Destination: Mars," a mixed-reality experience that lets users explore the Martian surface, opened to the public at Kennedy Space Center's visitor complex in Florida.

High-def holograms offer a striking simulation of standing on another planet.

THE CRAFT OF CREATION

Aaron Parness studied creative writing in school, and admires tales of magical realism by authors like Gabriel García Márquez. A penchant for sagas that combine the mundane with the fantastic seems fitting for someone who now creates robots modeled after geckos, lemurs and other creatures.

“Cockroaches can move 30 times their body length in a second, on any terrain,” he says. “That’s equivalent to humans running 100 miles per hour. Pit vipers have better thermal sensors than our infrared telescopes. Whale fins are more efficient at moving through fluids than our submarines.”

These amazing abilities aren’t magic, but based on fundamental principles of physics. That’s the challenge of Parness’s Robotic Prototyping Lab at JPL: to build machines that leverage those techniques, rather than trying to make copies of the animals themselves.

“We’re 50 years away from being able to perfectly replicate the hairs on a gecko’s foot pads,” he says. “Biology is immensely complicated.”

Parness first got into bio-inspired bots while working on his PhD at Stanford University, where one of his projects was to create gloves for Special Forces soldiers to scale walls like Spider-Man. Once he joined JPL, his focus shifted to climbing the canyons of Mars, or moving in the microgravity of asteroids and comets.

Parness has taken his team’s robots to volcanoes in Hawaii, caves in the Mojave Desert, and on microgravity flights to see how they cope in places too dangerous or difficult for people to go.

Because all of NASA’s rovers on Mars have been based on cars, he says, “we’ve been limited on where we could go. It’s like going to the Grand Canyon, but only driving around the parking lot. We haven’t yet gone to the really cool places.”

Thanks to the work of Parness’s lab, someday there could be a robot climbing like a gecko up a steep canyon of Mars, or scrabbling like a cockroach across the surface of an asteroid. Magical realism with a space-age twist.

PROFILE

AARON PARNESS

Taking stories to the world

PUBLIC ENGAGEMENT

JPL's missions are not only "quant" excursions framed by the algorithms and scatter plots of the science and engineering that define them. They are equally human adventures — dramas with emotional highs and lows, followed intently by a rapt public audience. Taking such stories to the world at large is an essential part of the Laboratory's mission. >

High-stakes events like Juno's orbit insertion bring the human drama of space exploration to the public.

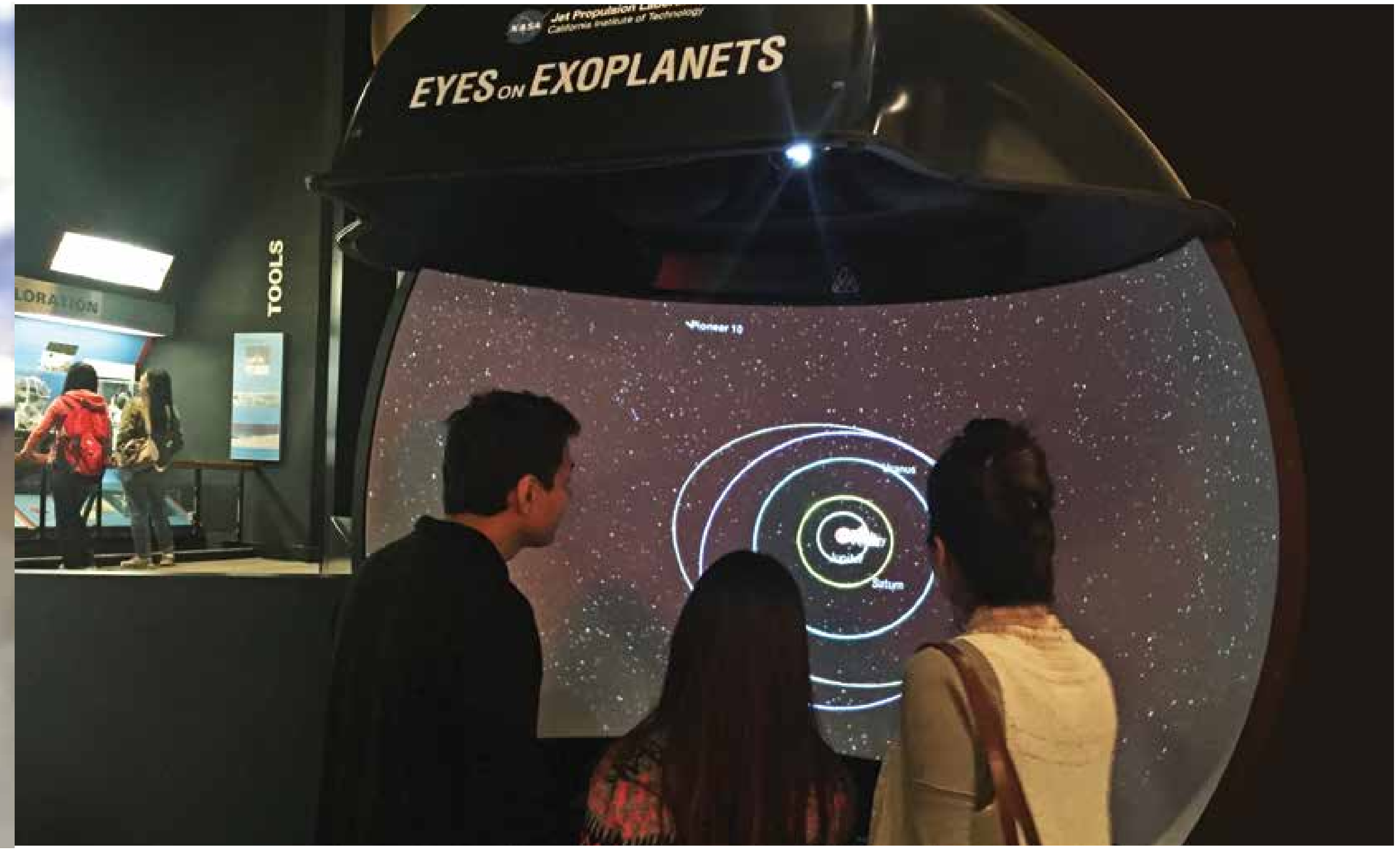
The Lab's open house weekend, "Explore JPL," always draws capacity crowds.

Nowhere was that more evident in 2016 than in the social media campaigns for JPL's airborne expeditions to Australia's offshore reefs and Greenland's glacier fields. Writers and videographers joined scientists on ships and planes to share stories of how science is done and the human faces behind the work. That in turn was shared with diverse audiences via social media including Facebook Live events and postings to Snapchat and Instagram.

JPL's leadership in engaging the public in NASA Earth science was also visible on Earth Day with "Earth 24/7," a campaign in which researchers from NASA centers, mission teams and academia were invited to post selfies and other pictures showing the human side of their research.

Another highly effective route for communicating science and engineering to the public was museum kiosks presenting JPL's "Eyes" visualization experiences — "Eyes on the Earth," "Eyes on the Solar System" and "Eyes on Exoplanets." After establishing four permanent kiosks at the Smithsonian's Air & Space Museum in Washington, JPL in 2016 gained a presence in New York City with two kiosks at the Intrepid Museum. They join kiosks at 16 museums and science centers in 11 states around the country.

On the web, NASA's Global Climate Change site created and managed by JPL achieved a key milestone when its popularity and reputation caused it to become the number one search result on Google for those seeking information on climate change. As of 2016, JPL's Webby Award-winning "Earth Now" app for iPhone and Android had received more than 1.6 million downloads from iTunes and Google Play.



Visitors to the National Air and Space Museum enjoy the interactive experience at one of several JPL "Eyes" kiosks.

MAJOR EXTERNAL AWARDS

Blaine Baggett
International Academy of Astronautics
Elected Member

David Bayard
Asian Journal of Control
Best Paper of the Year

James Benardini
White House
Early Career Award for Scientists and Engineers

Nacer Chahat
Antenna and Propagation Society, Institute of Electrical and Electronics Engineers
Elected Senior Member

Janis Chodas
International Academy of Astronautics
Elected Member

Richard Cook
International Academy of Astronautics
Elected Member

Dawn Project Team
National Aeronautic Association
Robert J. Collier Trophy

Dawn Project Team
National Space Club
Nelson P. Jackson Award

Matt Derenski
Federal Computer Week Magazine
Rising Star

< An infrared view of Beihai, China, captured by the ASTER instrument on NASA's Terra satellite.

Tom Farr
California Department of Water Resources
Remote Sensing and Drought Science Service Award

Eric Fielding
American Geophysical Union
Ivan I. Mueller Award

Robert Green
International Academy of Astronautics
Elected Member

David Halpern
Committee on Space Research
Distinguished Service Medal

Larry James
International Academy of Astronautics
Elected Member

Cathleen Jones
California Department of Water Resources
Remote Sensing and Drought Science Service Award

JPL Facilities Maintenance and Operations Group
Association of Energy Engineers
Energy Project of the Year

JPL Facilities Maintenance and Operations Group
U.S. Department of Energy
Federal Energy Management Program Award

JPL Information Technology Directorate
CIO Magazine
CIO 100 Honoree

JPL Rideshare Program
Los Angeles County Metropolitan Transportation Authority
Diamond Award

Zhen Liu
California Department of Water Resources
Remote Sensing and Drought Science Service Award

Keyur Patel
International Academy of Astronautics
Elected Member

JT Reager
National Oceanic and Atmospheric Administration
David Johnson Award

Virendra Sarohia
France Ministry of Education
Palmes Académiques

Peter Theisinger
American Astronautical Society
Space Technology Award

Peter Theisinger
National Air and Space Museum
Trophy for Lifetime Achievement

Slava Turyshev
International Academy of Astronautics
Elected Member

Yuan Wang
American Geophysical Union's Atmospheric Sciences Section
James R. Holton Award

Josh Willis
American Association for the Advancement of Science
Public Engagement Fellow

Cinzia Zuffada
Order of Merit of the Italian Republic
Degree of Knight

MAJOR CONTRACTOR PARTNERS

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Desktop Institutional Computing, InSight, Juno, Mars 2020, Mars Odyssey, Mars Reconnaissance Orbiter, Mars Science Laboratory, Rosetta, Spitzer Space Telescope

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Harris Corp.
Deep Space Network Operations

Applied Physics Laboratory, Johns Hopkins University
Europa, Mars 2020, Mars Reconnaissance Orbiter, Mars Science Laboratory

Airbus
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Emcor Government Services Inc.
Facilities Maintenance and Operations

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Airborne Visible/Infrared Imaging Spectrometer, Euclid, Europa Mission, Near-Earth Object Camera, Orbiting Carbon Observatory 2

Northrop Grumman Systems Corp.
Atmospheric Infrared Sounder, James Webb Space Telescope Mid-Infrared Instrument, NASA-ISRO Synthetic Aperture Radar

A 34-meter-diameter (112-foot) antenna at the Deep Space Network's complex in Goldstone, California.

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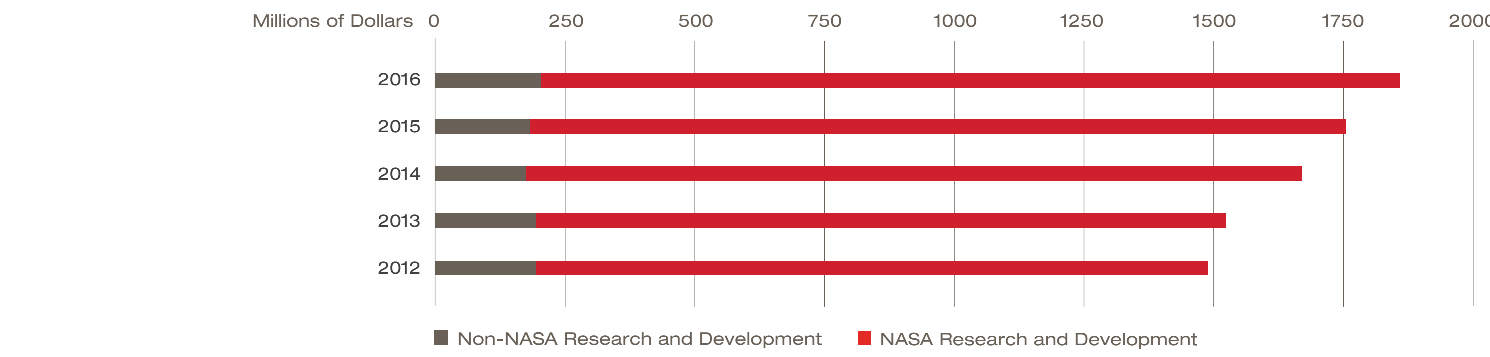
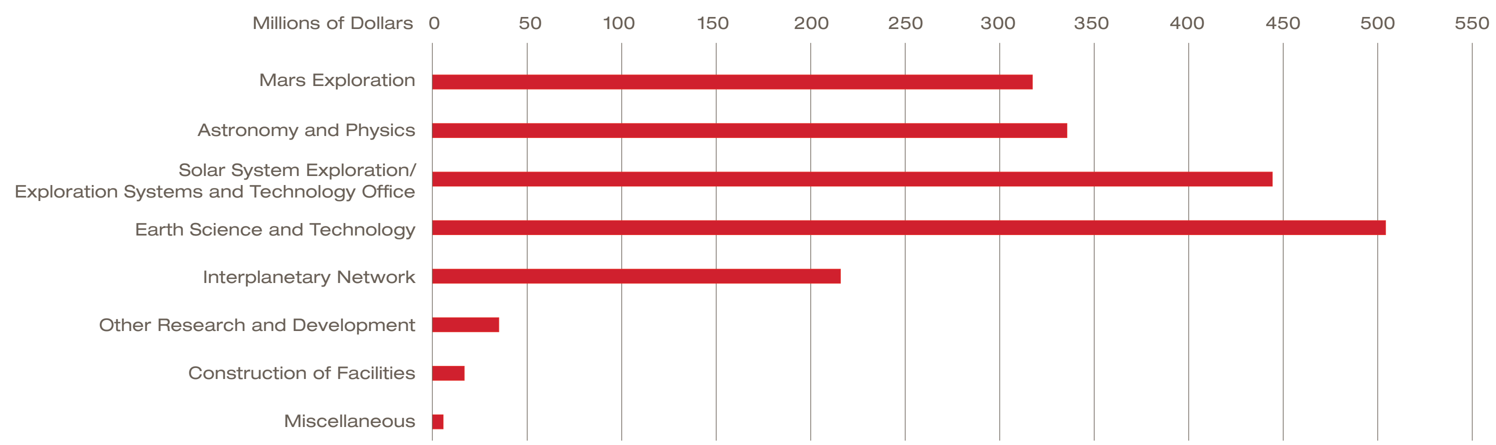
BUDGET AND WORKFORCE

Year-to-Year Budget

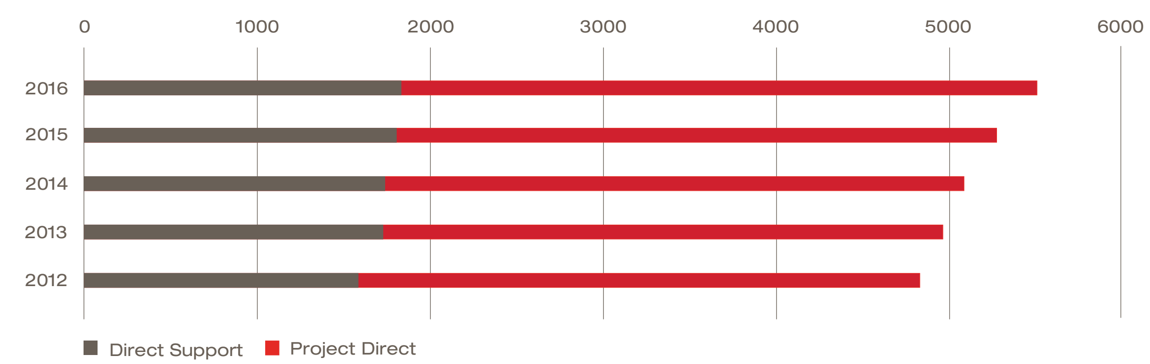


2016 Budget



JPL Personnel

Full-Time Equivalents



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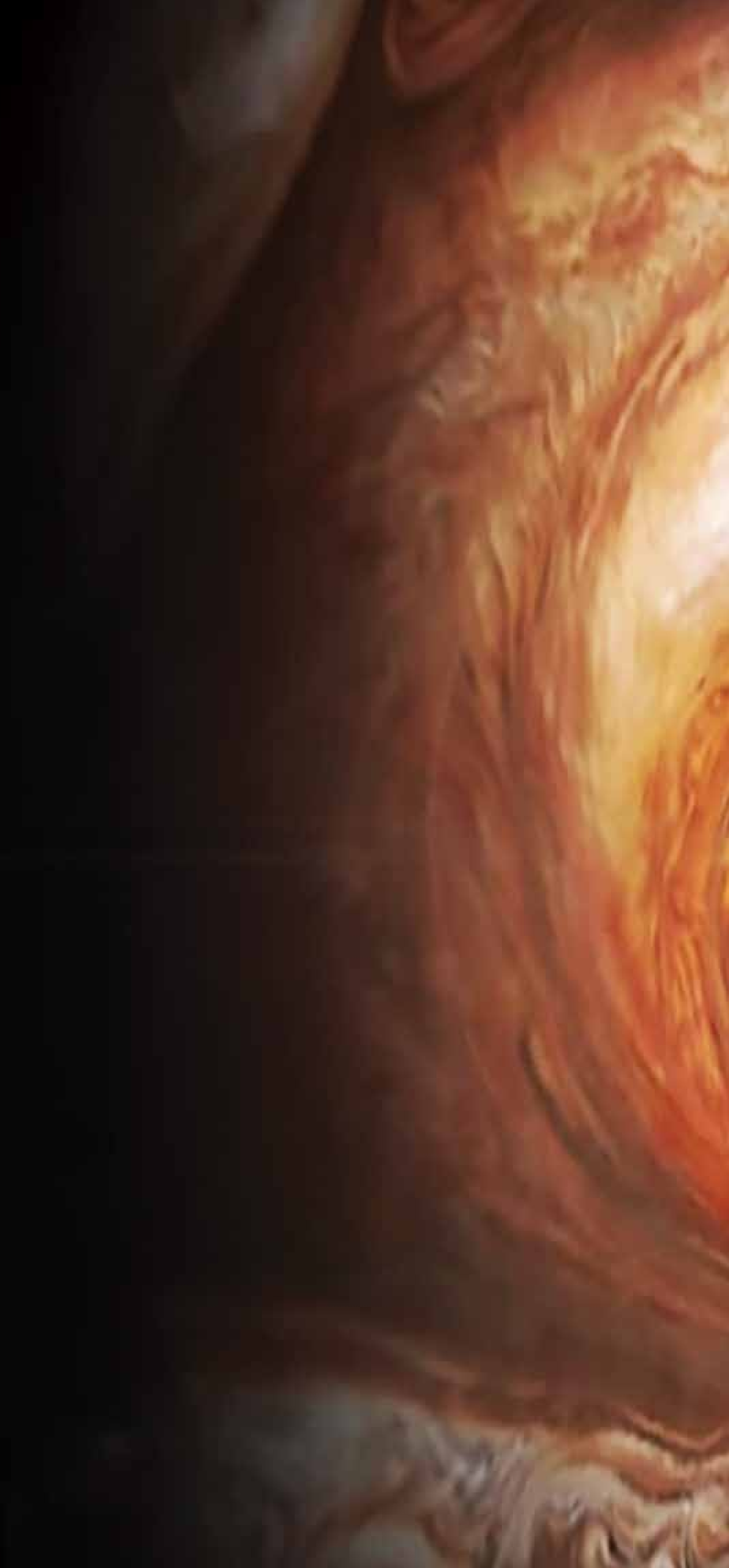
BACKGROUND
Dunes of gypsum partially encircling Mars' north pole in a region called Olympia Undae, as viewed by Mars Reconnaissance Orbiter.



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JPL 400-1653 03/17