09.2021

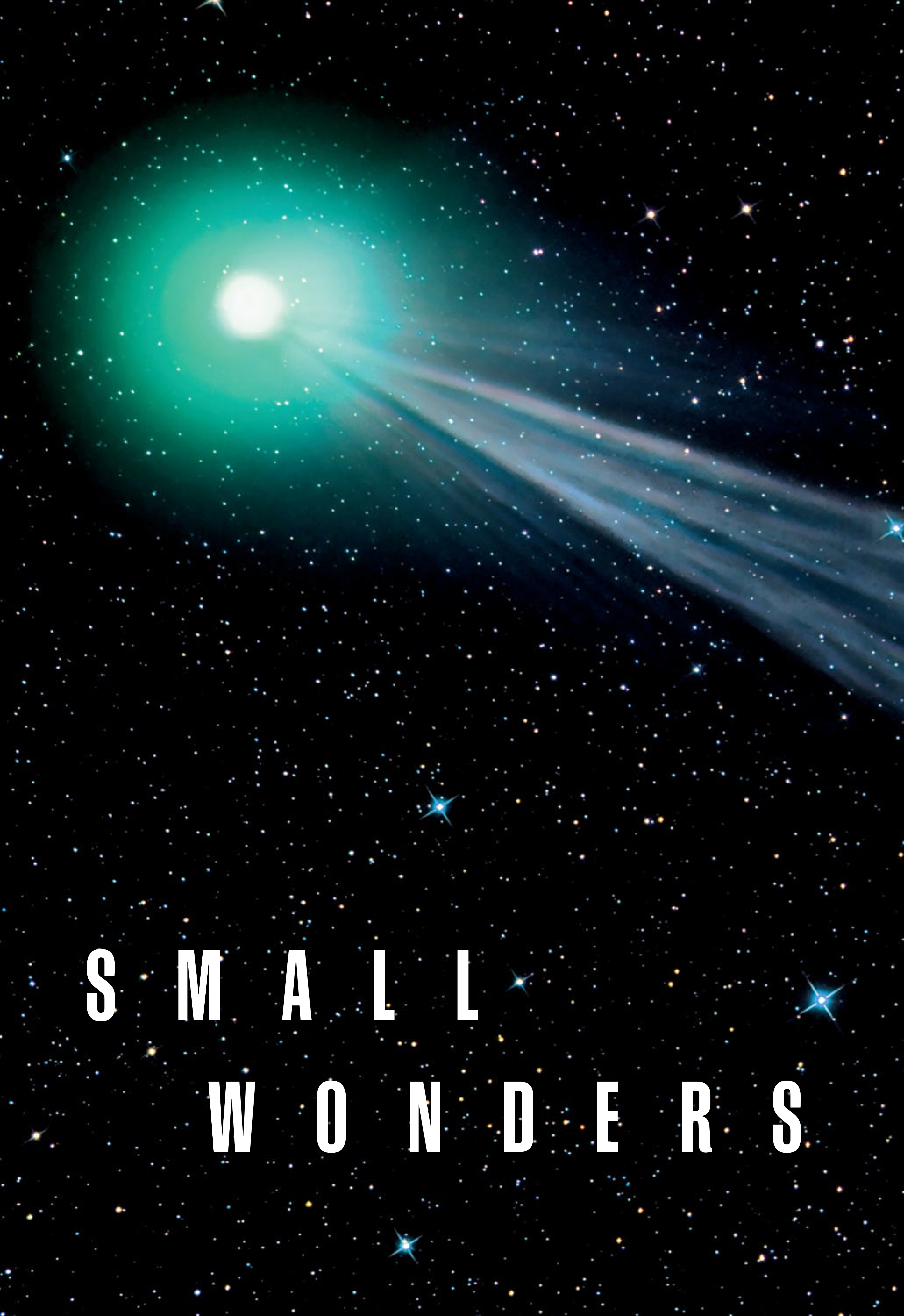
FREE POSTER

NATIONAL GEOGRAPHIC

MYSTERIES OF THE SOLAR SYSTEM

What new technology reveals about the millions of asteroids, comets, dwarf planets, and other objects orbiting our sun

Launching in October, NASA's Lucy spacecraft eventually will fly by asteroids near Jupiter.


SMALL
WONDERS

Modern astronomy is giving us unprecedented views of the tiny objects littering our solar system. These small bodies are yielding clues to the UNIVERSE'S BIGGEST MYSTERIES.

BY MICHAEL GRESHKO

In 2015 comet C/2014 Q2 Lovejoy—seen here in a two-photo mosaic—neared the sun for the first time in millennia. Lovejoy likely hails from the Oort cloud, a distant shell of icy objects thought to surround the solar system. It's one of the roughly 4,000 known comets among the billions estimated to exist in our cosmic backyard.

RUNNING ON SUN

A solar array for NASA's Lucy spacecraft unfurls as it is tested at a Lockheed Martin facility in Colorado. Set to launch in October, Lucy will need two of these arrays to generate power during its 12-year mission to explore Jupiter's Trojan asteroids. These ancient swarms, which orbit the sun alongside the giant planet, may hold clues to the solar system's original layout.

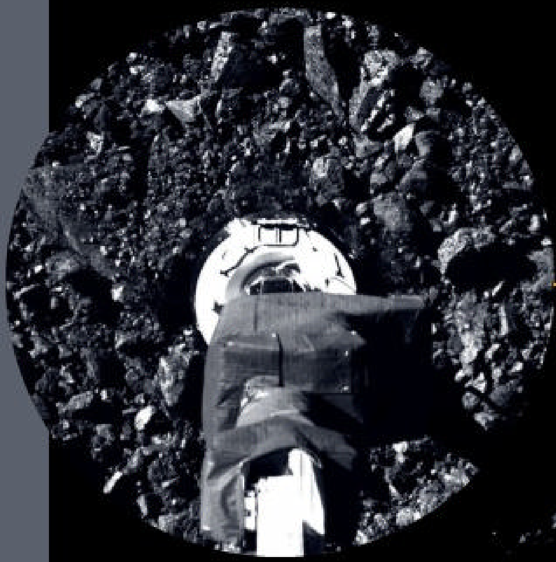
PATRICK H. CORKERY, LOCKHEED MARTIN

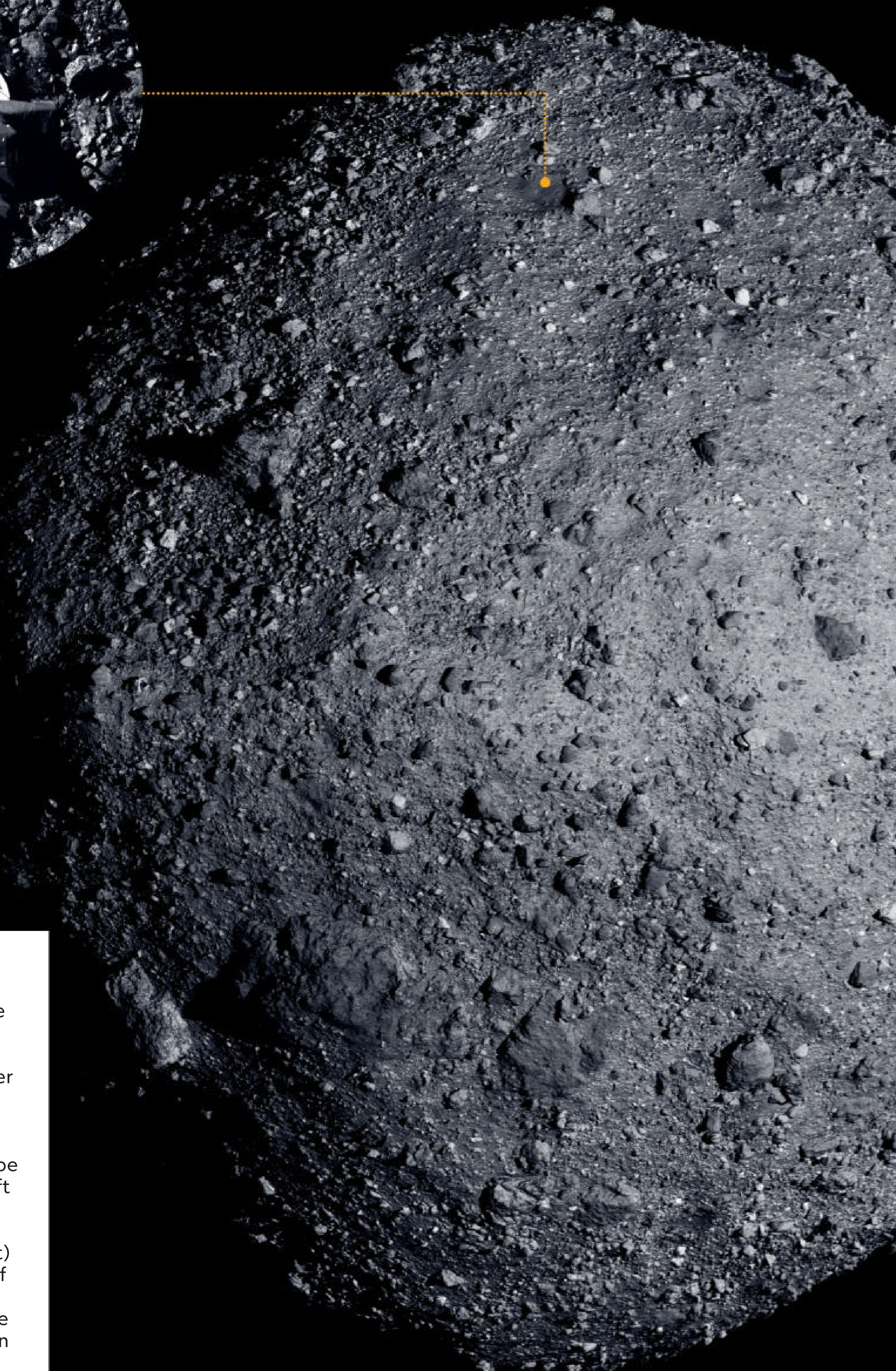
OPENING IMAGE: VELIMIR POPOV AND EMIL IVANOV AT THE IRIDA OBSERVATORY

DOWN TO EARTH

On December 6, 2020, a capsule released by the Japanese spacecraft Hayabusa2 landed among the silvery saltbushes and terra-cotta soil of the Australian outback. The container held debris the spacecraft had collected from the near-Earth asteroid Ryugu in 2019. The ancient material now resides at the Extraterrestrial Sample Curation Center (right) in Sagamihara, Japan. Scientists hope it will help unlock secrets about early planet formation and perhaps even the origins of life on Earth. Although Hayabusa2's cargo has returned, the spacecraft is now on an extended mission that will take it to another asteroid in 2031.

JAPAN AEROSPACE EXPLORATION AGENCY (LEFT); NORIKO HAYASHI (RIGHT)

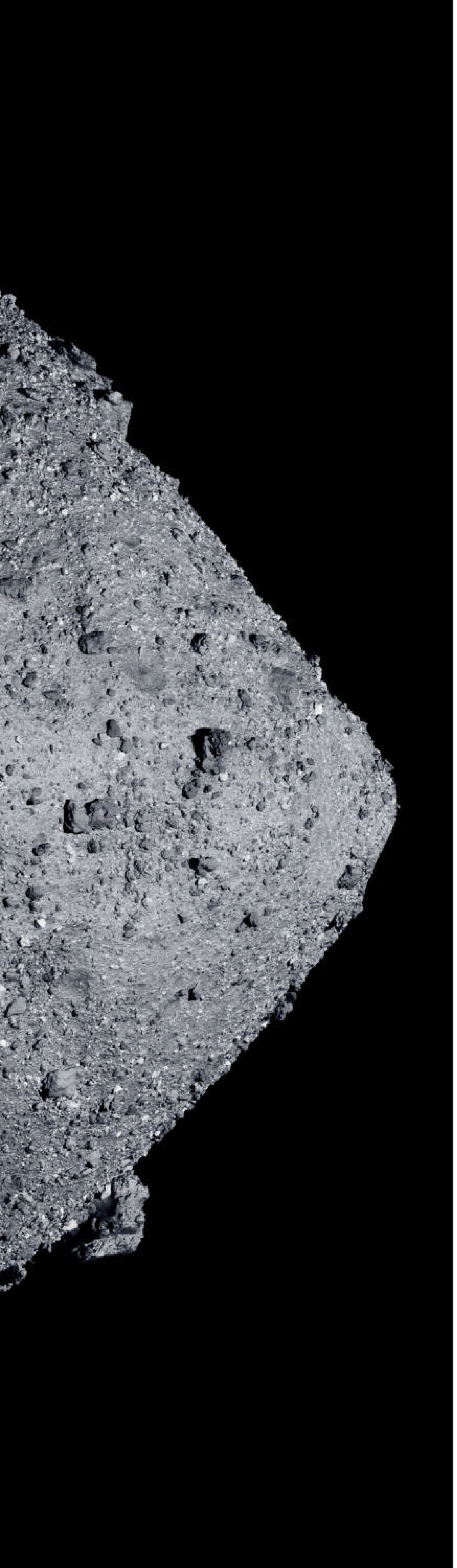




TARGET ACQUIRED

As wide as the Empire State Building is tall, the asteroid Bennu is the smallest body ever orbited by a spacecraft. On October 20, 2020, Bennu became the third asteroid to be sampled by spacecraft when NASA's OSIRIS-REx plunged its arm into the surface (inset) and collected some of its dust and pebbles. A capsule carrying the sample should land on Earth in 2023.

VISUALIZATION BY KEL ELKINS, NASA GODDARD SPACE FLIGHT CENTER; NASA GODDARD SPACE FLIGHT CENTER/UNIVERSITY OF ARIZONA (INSET)



DANTE LAURETTA IS SERENE AS HE PREPARES FOR THE 17 SECONDS HE'S WORKED TOWARD FOR THE PAST 16 YEARS.

Lauretta, a University of Arizona planetary scientist, is transfixed by a monitor showing three simulated views of a rubbly, top-shaped object floating in a sea of stars. That's the asteroid known as 101955 Bennu. He's watching it while perched on an upholstered metal stool inside an unassuming building in Littleton, Colorado. With its cinder-block hallways, pop-out ceiling panels, and the occasional wasp problem, the building could be mistaken for a run-of-the-mill office suite. But the spacecraft decals on the walls and the labels above each cubicle—Electrical Power; Telecom; Guidance, Navigation & Control—reveal its true function: mission control at Lockheed Martin Space.

It's 1:49 p.m. mountain time on October 20, 2020, and the screen shows Bennu sitting within a green hoop that represents the orbit of a NASA spacecraft with a mouthful of a name: the Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer—OSIRIS-REx for short. In less than three hours, this robotic emissary will attempt to descend and touch Bennu for the first time, hopefully trapping a sample of extraterrestrial dust and pebbles for return to Earth.

PLANET NURSERY

Near-infrared images, captured by the Gemini South telescope in Chile, reveal planetary leftovers around other stars. Each disk of icy, rocky debris surrounds a young star (blocked out here). Many disks have inner "holes" likely carved out by newly formed planets. These disks resemble our solar system's Kuiper belt, which lies beyond the orbit of Neptune.

COMPOSITE FROM FIVE IMAGES BY INTERNATIONAL GEMINI OBSERVATORY/NOIRLAB/GPIES/ T. ESPOSITO, UC BERKELEY

Launched in 2016, OSIRIS-REx h
the sun twice to catch up with Benn
more than 200 million miles away on
October day. At roughly a third of a
Bennu is the smallest celestial body a
has ever orbited. Its surface is so rugg
ta's team spent a year mapping it to
place to descend. All this buildup sh
today's main event a tense moment,
late stage of the billion-dollar missio
seems at peace.

"The spacecraft is in a really g
today," he tells me.

Why go through all this stress an
a few pounds of dust and rubble? F
the asteroid's building blocks form
the solar system's earliest days, mo
billion years ago. These rocks, which
they contain carbon, represent a prist
of how the planets formed and perh
Earth got the starter materials for life
ically, it's literally pay dirt," Lauretta

But just as Bennu carries the stuff of
also has the power to destroy. Bennu c
enough to Earth that astronomers beli
a small but serious chance—one in 2,7
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samples OSIRIS-REx brings back coul
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that could release more than two mi
the energy of the ammonium nitrate
rocked Beirut a year ago—enough to
a state or province, possibly even a c

On a grander scale, Bennu and O
symbolize two parallel revolutions
astronomy that are upending old con
the solar system. Today's telescopes ca
small, faint objects than ever before
astronomers to survey the skies and
cosmic population that surrounds the
ets. Twenty years ago, humans knew
a hundred thousand celestial bodies
system. By early 2021, we'd catalog
more than a million objects orbiting

At the same time, space agencies a
world have developed the tools and te
to visit and explore these worlds—and
pieces of them back to Earth for clos

The stakes are far from abstract.

The picture of the solar system we
in school seems to have a logical ar
But astronomers and planetary scie
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since by the looks of it, it's extremely difficult to explain how Uranus and Neptune could have formed where they orbit today. Our cosmic home appears to be missing some of the most common types of planets that orbit alien stars. And as of 2021, Earth is the only known harbor for life.

So how, exactly, did our solar system end up here—and give rise to its inhabitants?

Small bodies such as Bennu were long dismissed as mere leftovers in the process that created the planets. But now researchers know how important these bodies are in the search to answer such massive questions. Like Bennu, many are time capsules, essentially unchanged since the birth of our sun. Others could similarly pose a threat to life on Earth. By tracking, visiting, and sampling these primordial worlds, we're finally getting a chance to see where we came from—and to hopefully stop these objects from destroying who we've become.

HUMANKIND'S INTEREST in small bodies—astronomer-speak for every natural object orbiting the sun that isn't a planet, dwarf planet, or moon—has been with us as long as there have been people looking up. For millennia, cultures around the world have spotted the comets and meteors visible in the night sky and treated them as important omens. There was only so much people could do to learn more, though, because small bodies reflect very little sunlight and therefore are hard to find in the blackness of space.

By the dawn of the 20th century, astronomers had found roughly 500 asteroids orbiting the sun, starting with the 1801 discovery of Ceres. The pace of discovery really began to crank up in the 1980s and '90s as telescopes improved. In 1992 astronomers spotted the first world—aside from Pluto and one of its moons—that is beyond Neptune's orbit, confirming theories of the solar system's outer zone now called the Kuiper belt. Today astronomers know this far-flung region is filled with thousands—perhaps hundreds of thousands—of icy bodies.

But if you had to pinpoint when the small-body frenzy began, a reasonable choice would be March 11, 1998. That's when the U.S.-based Minor Planet Center, the world's official repository of all asteroid and comet orbits, issued an ominous-sounding press release: An asteroid

DUSTY BEGINNINGS

In the wake of our sun's formation, a cloud of dust and gas was left swirling around the infant star. Gradually these materials began to clump together, forming the beginnings of planets. In the celestial chaos, these objects collided, sometimes forming larger bodies and other times being broken up entirely. Over four billion years later, countless bits of leftover rubble remain trapped in the gravity of our sun and its planets.

MULTITUDES OF MINORS

Leftover fragments of planetary building blocks orbit the sun in the form of asteroids, comets, and dwarf planets. Ranging from pristine to geologically active, these small bodies offer clues to our solar system's history through their composition, orbit, and behavior.

Rocky residuals

Objects that orbit closer to the sun are mostly small and rocky. Jupiter's gravity likely prevented the formation of a planet in the main asteroid belt and caused early protoplanets to collide and break apart. Their combined mass is less than that of Earth's moon.

EROS: BRIGHT AND STONY

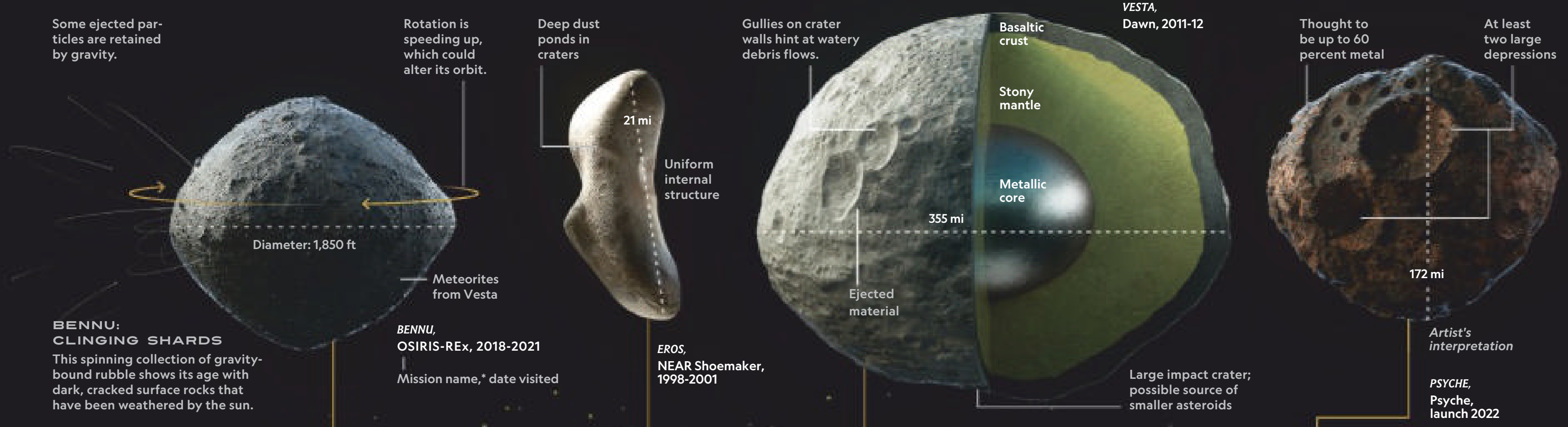
Eros is one of thousands of asteroids that cross Earth's orbit and may be fragments from larger asteroids or the burned-out remnants of comets.

VESTA: INTACT PROTOPLANET

Models suggest that as many as a hundred emerging planets started to form. Vesta, the largest asteroid, appears to be the only intact survivor. Craters, fractures, and lava flows scar this object's surface.

PSYCHE: RARE ORB

Did collisions rip off a rocky layer surrounding the metallic core of an ancient developing planet? An upcoming mission will investigate whether that's Psyche's origin story.



BENNU: CLINGING SHARDS

This spinning collection of gravity-bound rubble shows its age with dark, cracked surface rocks that have been weathered by the sun.

BENNU, OSIRIS-REx, 2018-2021

Mission name,* date visited

EROS, NEAR Shoemaker, 1998-2001

PSYCHE, Psyche, launch 2022

SCATTERED ORBITS

Scientists have identified over a million objects close to Earth. Celestial bodies farther from the sun—estimated in the trillions—are more difficult to observe due to their distance and darker, less reflective surfaces.

Hazard zone

Large asteroids and comets that orbit close to Earth are considered potentially hazardous. Over 2,100 such objects are under experts' watchful eyes.

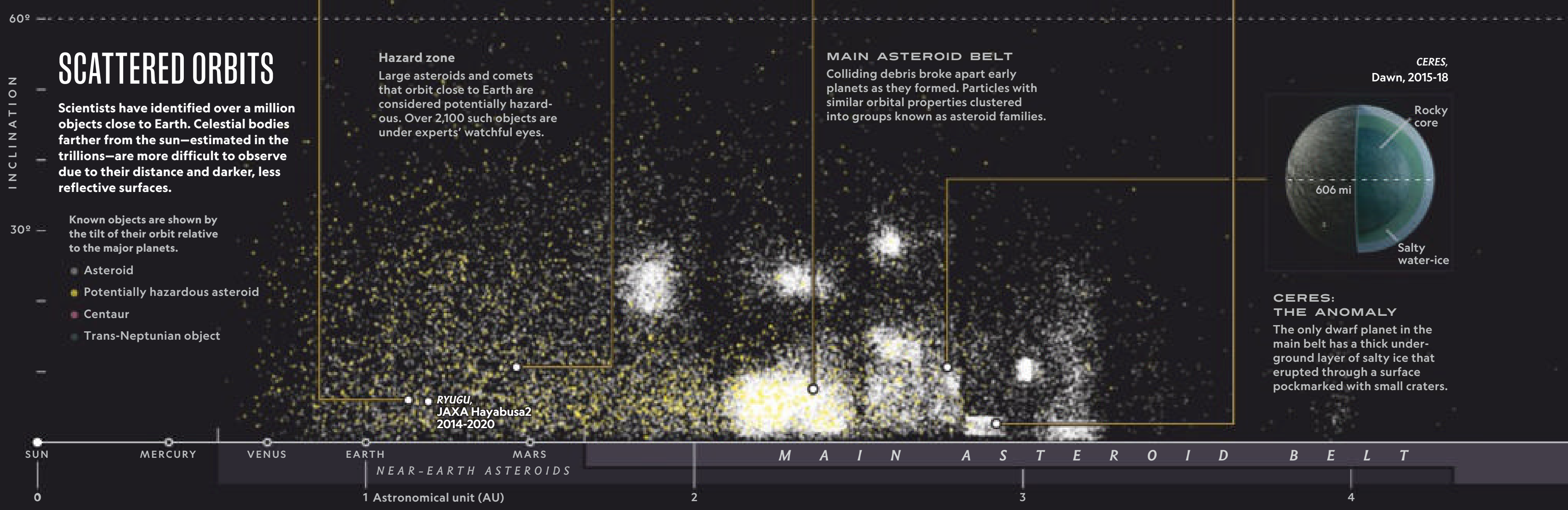
MAIN ASTEROID BELT

Colliding debris broke apart early planets as they formed. Particles with similar orbital properties clustered into groups known as asteroid families.

CERES, Dawn, 2015-18

CERES: THE ANOMALY

The only dwarf planet in the main belt has a thick underground layer of salty ice that erupted through a surface pockmarked with small craters.

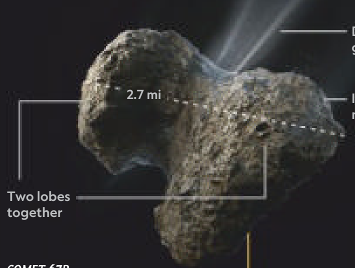


BODIES NOT TO SCALE. *NASA MISSION UNLESS OTHERWISE IDENTIFIED. †OBJECT COUNT AS OF JUNE 30, 2021.

1,099,978 BODIES HAVE BEEN CATALOGED IN OUR SOLAR SYSTEM. TRILLIONS HAVE YET TO BE IDENTIFIED.*

Beyond the frost line

At this distance from the sun, water begins to condense into ice. Bodies typically are icier and gassier, with more elliptical orbits. Out here many objects are paired, both small and planet-size.



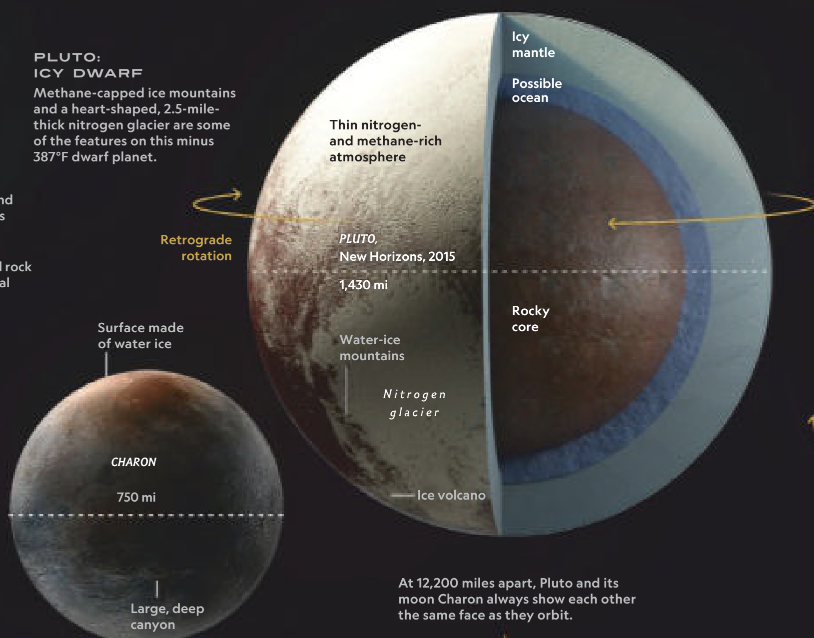
COMET 67P CHURYUMOV-GERASIMENKO,
ESA Rosetta, 2014-16

COMET: ICY CONTACT

Porous, pitted, and spewing dust-filled water vapor, comets also have been shown to sometimes host life-building compounds.

PLUTO: ICY DWARF

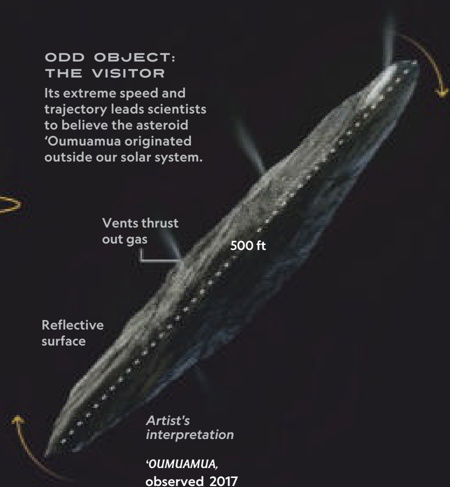
Methane-capped ice mountains and a heart-shaped, 2.5-mile-thick nitrogen glacier are some of the features on this minus 387°F dwarf planet.



At 12,200 miles apart, Pluto and its moon Charon always show each other the same face as they orbit.

ODD OBJECT: THE VISITOR

Its extreme speed and trajectory leads scientists to believe the asteroid 'Oumuamua originated outside our solar system.



'OUMUAMUA,
observed 2017

How we know

Sometimes when objects pass in front of a brighter body, information about their size and shape can be revealed.

JUPITER'S TROJANS,
Lucy,
launch 2021

Trojans

Millions of asteroids are balanced between the pulls of Jupiter and the sun.

Centaurs

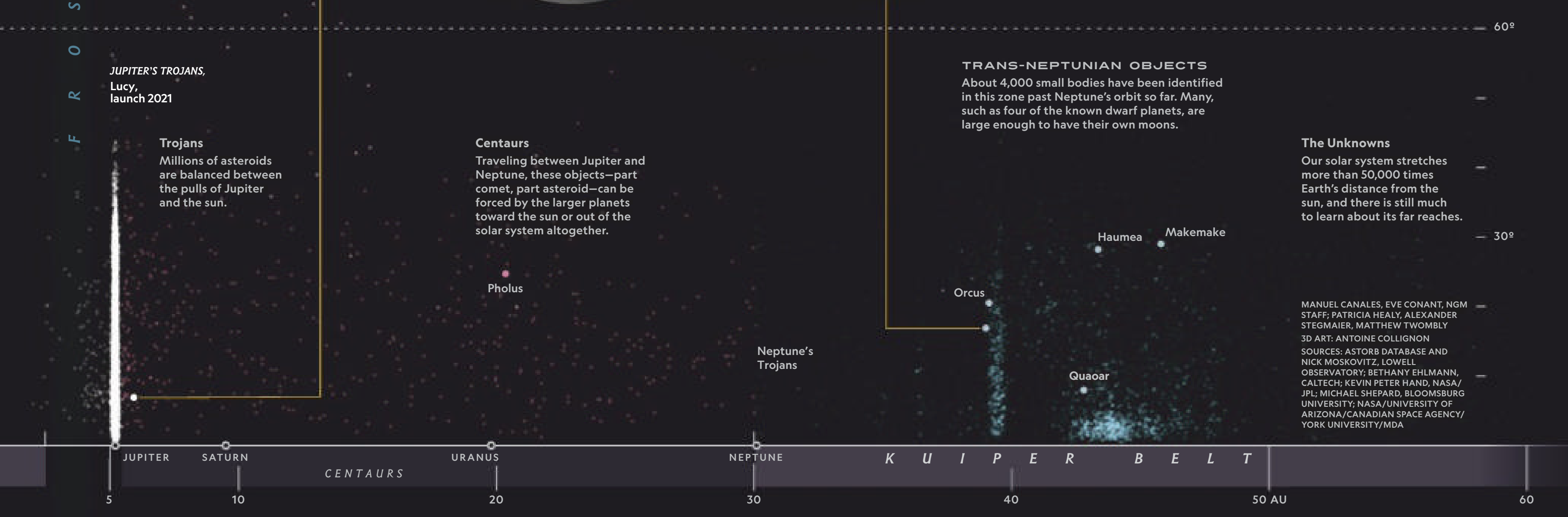
Traveling between Jupiter and Neptune, these objects—part comet, part asteroid—can be forced by the larger planets toward the sun or out of the solar system altogether.

TRANS-NEPTUNIAN OBJECTS

About 4,000 small bodies have been identified in this zone past Neptune's orbit so far. Many, such as four of the known dwarf planets, are large enough to have their own moons.

The Unknowns

Our solar system stretches more than 50,000 times Earth's distance from the sun, and there is still much to learn about its far reaches.



MANUEL CANALES, EVE CONANT, NGM STAFF; PATRICIA HEALY, ALEXANDER STEGMAIER, MATTHEW TWOMBLY

3D ART: ANTOINE COLLIGNON

SOURCES: ASTORB DATABASE AND NICK MOSKOVITZ, LOWELL OBSERVATORY; BETHANY EHLMANN, CALTECH; KEVIN PETER HAND, NASA/JPL; MICHAEL SHEPARD, BLOOMSBURG UNIVERSITY; NASA/UNIVERSITY OF ARIZONA/CANADIAN SPACE AGENCY/YORK UNIVERSITY/MDA

MANUEL CANALES, NGM STAFF; PATRICIA HEALY, ALEXANDER STEGMAIER
ART: ANTOINE COLLIGNON
SOURCES: KEVIN PETER HAND, NASA/JPL; NICK MOSKOVITZ, LOWELL OBSERVATORY; MICHAEL SHEPARD, BLOOMSBURG UNIVERSITY

discovered the previous December would come within 26,000 miles of Earth's surface in 2028, with a small chance it would hit the planet.

The story quickly made headlines around the world, and the news hit a public increasingly aware of how much damage an asteroid could deal. A few years earlier, geologists had identified the crater left by the asteroid that struck Earth 66 million years ago, killing off all the dinosaurs except birds. Was the incoming space rock the next Big One?

Astronomers raced to double-check their calculations. By the next day, Don Yeomans and Paul Chodas with NASA's Jet Propulsion Laboratory had figured out that the asteroid would sail harmlessly by Earth at a distance of 600,000 miles. Whew—crisis averted. Still, the back-and-forth cast a glaring spotlight on how little support there had been for finding killer asteroids.

By coincidence, the Hollywood blockbusters *Deep Impact* and *Armageddon* premiered just months after the affair, reinforcing asteroid impacts as the apocalypse du jour. In May 1998 Congress told NASA to find at least 90 percent of all asteroids at least six-tenths of a mile wide that come within 121 million miles of the sun, and to do it within a decade. By July NASA had designated an office to oversee the asteroid search.

Astronomers didn't just have political will on their side. They also had the right technology. By the late 1990s digital camera sensors had gotten big and sensitive enough to outperform the cumbersome glass plates used for decades to take pictures of the night sky. Telescopes suddenly could see smaller, fainter, and more distant objects. And because the new data arrived digitized, researchers could analyze them with computer software, simplifying the process.

Mike Brown, an astronomer at California Institute of Technology in Pasadena, saw firsthand what followed. In 2002 Brown and his colleagues decided to upgrade the 48-inch-wide telescope at California's Palomar Observatory with a large digital camera. When Brown aimed the instrument toward the Kuiper belt in hope of finding objects bigger and brighter than the region's few hundred known denizens, his team started discovering so many new worlds, "I just felt like things were falling out of the sky," he says.

Brown's discoveries included three objects that each were at least half as wide as Pluto, and one—named Eris for the Greek goddess of discord—that was more massive. So in 2006 the

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are today, such as the reddish object
which NASA's New Horizons probe
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hey probably don't feel gravitational
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d some astronomers suspect they
presence of an unseen planet several
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our best telescopes can tell us only
bout what all these strange objects
f, what they're doing, and the role
the evolution of the solar system. To
filling in the puzzle, humans needed
eces of the cosmos to Earth.

N ON DECEMBER 6, 2020, Shogo
s helicopter touched down in Austra-
era Prohibited Area, a 47,000-square-
of bush-stippled outback about 300
h of Adelaide. Over millennia, this
esert has seen many uses. Six Aborig-
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orning, the site served as a landing
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s prior, the Japan Aerospace Explora-
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etrieve a sample from the surface of an

RAIN OF ROCK?

Astronauts collected the first pristine samples from another world, including soil ejected from the moon's Copernicus crater (above), which was retrieved during the Apollo 12 mission (below). Those samples suggest the crater formed about 800 million years ago, possibly during intense asteroid showers that bombarded Earth and its natural satellite.

JAPAN AEROSPACE EXPLORATION AGENCY/SELENE (TOP); CHARLES CONRAD, JR., NASA (BOTTOM) asteroid. The Hayabusa mission rendezvoused with the asteroid 25143 Itokawa in 2005, but the sampling maneuver didn't go as planned. A capsule bearing only a light sprinkling of its dust grains landed in Woomera in 2010. Its successor, Hayabusa2, set off in 2014 to the near-Earth asteroid 162173 Ryugu—and did its best impression of a superhero's bottomless utility belt once it arrived at its target.

Inside the spacecraft, engineers had packed a suite of scientific instruments, a lander, three rovers, an impactor designed to make an artificial crater, and a breakaway camera that filmed the blast while the main spacecraft moved out of range for its own safety. Those accessories aided Hayabusa2 in its ultimate goal: twice alighting on Ryugu, firing a pellet into its surface, and collecting the schmutz that sprayed outward.

Now, 5.4 grams of jarringly dark grains and pebbles are in a lab outside Tokyo, shepherded there from the Australian outback by Tachibana's team. This is humankind's first up-close look at Ryugu's surface and subsurface, and upcoming studies will provide invaluable records of the solar system's history.

Until missions such as Hayabusa2, scientists relied on meteorites that had fallen to Earth to delve into the solar system's origins. Some of these primordial lumps indicated that the asteroids that shed them contain a surprising amount of water-bearing minerals, as well as the types of carbonaceous chemistry that can give rise to some of life's building blocks. But even these extraordinary insights come with a catch: Meteorites aren't completely pristine, having gotten to Earth's surface only after surviving a fiery descent through our atmosphere.

BY VISITING ASTEROIDS, SCIENTISTS HOPE TO LEARN HOW EARTH'S SURFACE BECAME AN OASIS FOR LIFE, EVEN THOUGH THE PLANET FORMED SO CLOSE TO THE SUN.

By visiting asteroids in space and sampling them, scientists may help solve an enduring mystery: How did Earth's surface become an oasis for life, even though the planet formed so close to the sun? As it took shape more than 4.5 billion years ago, our home world went through a scorching, hellish youth. Yet here we sit, our pale blue dot sloshing through space as a biological haven that depends on water and carbon.

Some research suggests that despite baking in the inner solar system, the infant Earth's building blocks could have contained enough hydrogen to account for much of our planet's water. But meteorites and impact craters across the solar system point to another, paradoxically violent source of hydration: bombardment by asteroids and comets. So far, missions sent out to small bodies have provided tantalizing hints of these ancient impacts' boosts to Earth's prebiotic chemistry.

The 1,500 grains of Itokawa returned by the first Hayabusa mission show that the asteroid's minerals contain water that looks chemically similar to Earth's. And when the European Space Agency's Rosetta mission became the first spacecraft to orbit and land a probe on a comet, between 2014 and 2016, it revealed that up to a quarter of the comet's mass is made up of organic molecules formed by nonliving processes. It also showed that some of the material brought to an infant Earth may have been especially fragrant: Based on its chemical profile, the comet would smell like a noxious blend of rotten eggs, formaldehyde, and a horse stable's harsh fumes, with a dash of almond.

Clearly, small bodies aren't bit players in the epic saga of Earth's evolution—they're central characters. But we can't just think in terms of their utility to Earth. If anything, robotic missions have underscored that asteroids and comets are tiny worlds with terrains all their own. These objects cover such a wide range of shapes, sizes, and histories, "it's as if we suddenly have a million new kinds of worlds to explore," says Arizona State University planetary scientist Lindy Elkins-Tanton, who is principal investigator on a NASA mission to explore an oddly reflective, likely metallic asteroid called Psyche.

Beyond their makeup, the diverse movements of small bodies are revealing how important these worlds have been in shaping the star system we all call home.

THE SAME COLORADO BUILDING that houses OSIRIS-REx's mission control contains the cavernous room where engineers build other NASA missions—including a robotic paleontologist of sorts that soon will trek toward Jupiter. To see this spacecraft back in October, I put on my space-day best—a face mask and a slippery, head-to-toe "bunny suit" designed to prevent my clothes and skin from contaminating anything. Then I walk into a huge, cream-colored clean room humming with ventilation. Hal Levison and Cathy Olkin, scientists at the Southwest Research Institute in Boulder, join me.

Levison and Olkin are the principal and deputy principal investigators, respectively, on the first mission to explore Jupiter's Trojan asteroids, two swarms of primordial objects that lead and follow Jupiter in its orbit around the sun. The way Olkin and Levison see it, the Trojans are the solar system's fossils, so Olkin suggested they name the mission Lucy, in honor of the famous skeleton of *Australopithecus afarensis,* a distant ancestral cousin of *Homo sapiens*.

It's not just my first up-close look at this spacecraft; it's Levison's too. As it happens, the engineers building Lucy are testing a key mechanism while we're visiting. To keep the spacecraft's gaze fixed on its targets during a planned series of high-speed flybys, Lucy's instruments sit on a platform that, in turn, is mounted to the spacecraft's chassis via a dual-axis gimbal, not unlike the one that stabilizes handheld cameras. The entire mission rests on that one robotic limb. If it flexes incorrectly or at the wrong time, Lucy's instruments may collect blurred data—or at worst, stare into darkness.

We form a spaced arc around the rig, eager for the show. It moves slowly, methodically, and even this small motion delights Olkin and Levison. "It's alive! It's alive!" Levison jokingly exclaims. The pair's eyes stay glued to their team's creation as it stirs awake.

The Jupiter Trojans that Lucy will study present a dynamical riddle: They don't appear to have formed in place, but their orbits are extremely hard to enter because they are so similar to the giant planet's path around the sun. If today's small bodies were to try and invade Jupiter's turf like this, they'd most likely collide with the behemoth or get scattered by its gravity, possibly even getting kicked out of the solar system. So how did Jupiter acquire its entourage?

In 2005 Levison and his colleagues at the Côte d'Azur Observatory in Nice, France, published an influential hypothesis, now called the Nice model, which posits that the solar system began with many more small bodies than it has now, and that Jupiter, Saturn, Uranus, and Neptune formed closer to the sun than they currently orbit. As small bodies gravitationally tugged at the gas giants, the planets' orbits shifted until they slipped into an unstable configuration.

Suddenly, the planets are thought to have reeled and staggered, their orbits ballooning outward to their current positions, where Jupiter captured its Trojans. In the fray, many small bodies either scattered inward toward the sun or got ejected from the solar system. The inner planets, including Earth, may have felt the aftereffects as an increase in bombardments. "The solar system is really like somebody picked it up early on and shook it real hard," Levison says.

After launching this October, Lucy will fly by a series of target Trojans from 2027 to 2033. The bodies' color, composition, density, and cratering should help researchers figure out when and where each formed within the solar system, aiding similar estimates for the rest of the Jupiter Trojans. These data will throw down a gauntlet: To have a shot at being correct, future simulations of early solar system formation must replicate whatever patterns Lucy finds. Along the way, the spacecraft will snap the first resolved images of the Trojans humans have ever seen.

"This is the last stable population of minor planets that hasn't been explored," Olkin says. "The time is right."

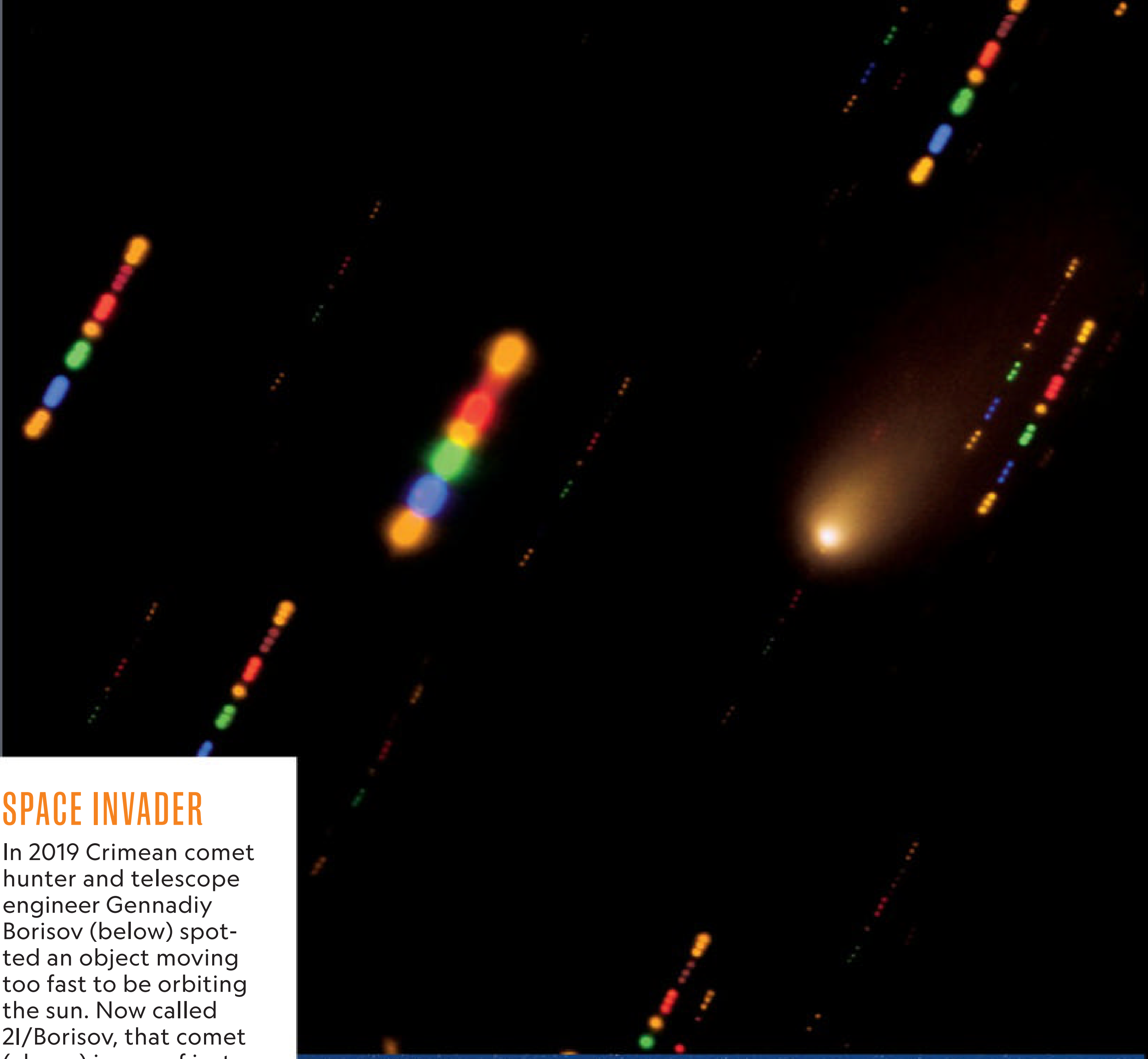
DESPITE ALL THIS PROGRESS, astronomers know we're only beginning to scratch the surface of what's out there—and what perks or perils might be lurking in the darkness.

When the Vera C. Rubin Observatory begins operations in 2023 in Chile, it will spend a decade mapping the southern night sky in stunning detail, most of it 825 times over. University of

EYE ON THE SKY

Engineers huddle beneath the two-foot-wide sensor array that will power the Vera C. Rubin Observatory's 3.2-gigapixel digital camera, the biggest ever built for astronomy. Under construction in Chile, the U.S.-funded observatory is expected to find about five million more asteroids, comets, and other small bodies after it goes online in 2023.

JACQUELINE ORRELL, SLAC NATIONAL ACCELERATOR LABORATORY



SPACE INVADER

In 2019 Crimean comet hunter and telescope engineer Gennadiy Borisov (below) spotted an object moving too fast to be orbiting the sun. Now called 2I/Borisov, that comet (above) is one of just two large bodies from other stars we've seen moving through the solar system. Thousands of interstellar interlopers are likely out there right now.

O. HAINAUT, EUROPEAN SOUTHERN OBSERVATORY (TOP); YULIA ZHULIKOVA (BOTTOM)

Washington astronomer Željko Ivezić, the survey's project scientist, often likens the survey to filming "the greatest movie of all time." Stitch all of its pictures together into a cosmic time lapse, and the resulting video could run in full-color HD for 11 months straight.

By the end of 2033, the Rubin Observatory is expected to dramatically increase the count of known small bodies. Its predicted haul includes another five million asteroids in the main belt, about 300,000 Jupiter Trojans, 40,000 objects beyond Neptune—and 10 to a hundred objects passing through our solar system that formed around alien stars, adding to the two astronomers have found since 2017.

For Michele Bannister, an astronomer at New Zealand's University of Canterbury, the Rubin Observatory's potential discoveries evoke awe. "We basically have been the kids on the seashore, standing there picking up a few shells and admiring how beautiful they are," she says, "and all around us is this vast ocean spreading out—which is suddenly going to be something we can go out and explore."

Mapping this celestial sea also is expected to find another 100,000 near-Earth asteroids that come within 121 million miles of the sun, some of which may be "potentially hazardous" like Bennu: objects wider than 500 feet, with orbits that take them within 4.7 million miles of Earth's path around the sun. If we've learned anything from COVID-19, let alone the climate and extinction crises, it's that the systems that undergird modern civilization are brittle. Now imagine throwing a big space rock at them.

"Obviously, near-Earth asteroids and comets, that's a much less likely problem compared to something like this pandemic," says Amy Mainzer, a University of Arizona planetary scientist who specializes in near-Earth asteroids. "But ... eventually, if you wait long enough, the unlikely events—they will happen."

Protecting Earth from such a fate won't require ragtag crews of nuke-toting astronauts, like in the movies. If astronomers can forecast a collision with enough notice, a zippy spacecraft could be launched in time to hit the asteroid and render its orbit harmless. In 2022 a NASA mission built and managed by the Johns Hopkins University Applied Physics Laboratory will try out this maneuver with a spacecraft called the Double Asteroid Redirection Test, or DART for short. DART will slam into a near-Earth asteroid's tiny moonlet at about 15,000 miles an hour, shortening the moonlet's orbit by as much as 10 minutes.

If DART proves a success, future humans may need to use a scaled-up version of this maneuver to keep Bennu in check. But first, much smaller pieces of Bennu will soar harmlessly through our atmosphere—thanks to that spacecraft being commanded from the Denver suburbs.

IT'S NOW 4:13 P.M. MOUNTAIN TIME on October 20, 2020, and the 17 seconds Dante Lauretta long awaited have come and gone—to his utter delight.

Two minutes earlier, he and his team received word that OSIRIS-REx was within five meters of Bennu's surface, and that the spacecraft's onboard hazard-detection system had given it the green light to proceed. Wearing a clear plastic mask to show more of his face under COVID-19 protocols, Lauretta breaks into a smile. Asked how he feels, he comes up with just one word: "Transcendental."

Systems engineer Estelle Church then confirms that the commands she sent have been executed. Millions of miles from Earth, dodging boulders bigger than houses, OSIRIS-REx has collected its bounty and is backing away.

The tip of OSIRIS-REx's sampling arm got so packed with debris that it jammed open, and the team had to rush to seal the leaking container within its return capsule. As a result, they don't know how much of Bennu they'll be bringing back to Earth when OSIRIS-REx drops off the capsule in 2023. But they suspect it'll be plenty, and that a closer look at its chemistry will shake up our understanding of biological beginnings.

"The likelihood that there's life elsewhere in the galaxy, even in the universe—we're gonna understand that a lot better," Lauretta says.

We're made of star stuff, as the old Carl Sagan adage goes. But as products of the solar system, we also could see ourselves as Bennu brothers, Psyche sisters, comet cousins—kin to the asteroids and comets that chronicle our deepest histories. In a sense, we too are the sun's small bodies: endlessly diverse and beautiful, bearing the secrets of life itself. □

Michael Greshko is a staff science writer for *National Geographic*.