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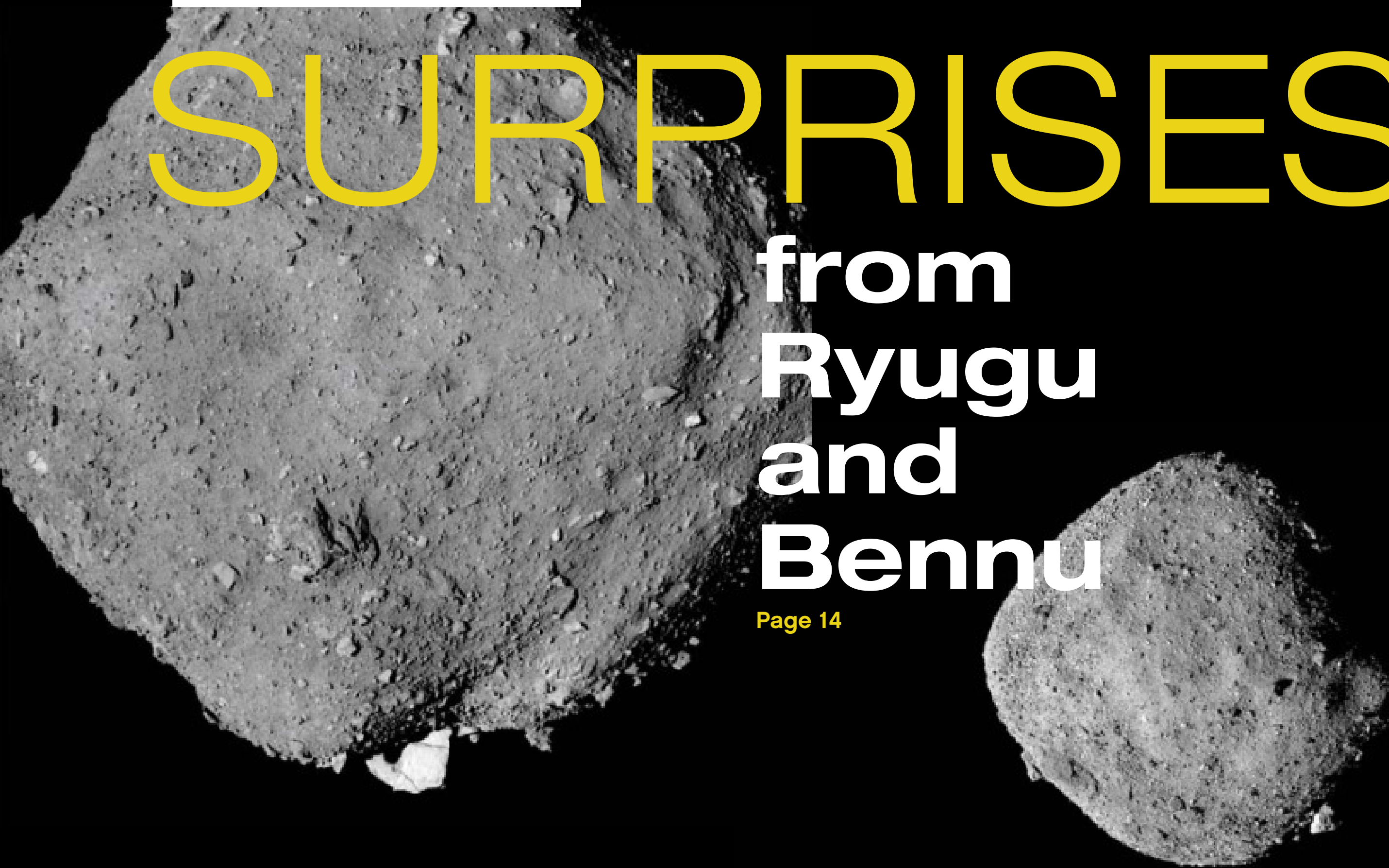
SKY & TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

MAY 2020

ASTEROID RECON



SURPRISES from Ryugu and Bennu

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The two spacecraft sent to Ryugu and Bennu have unveiled asteroids with formidable surfaces and mysterious histories.

Carl Hergenrother's brain was fried. He'd been awake all night, writing up results for a morning presentation at the science team meeting for NASA's OSIRIS-REX mission, which had arrived at asteroid 101955 Bennu just a month prior. Running on maybe a half hour of sleep, he decided the only thing his mind was good for was to blink through the week's backlog of navigation images and check for anything interesting.

He watched in a daze as Vega and Lyra went by, then Orion, then distant Earth and its Moon. Suddenly, he hit upon an image of what looked like a dense star cluster sitting just off the asteroid's limb. Enough of a backyard astronomer to quickly tell one cluster from another, Hergenrother (University of Arizona) knew at a glance that he wasn't looking at one of the well-known celestial groupings such as the Coma or Hyades clusters. In fact, he didn't know of any cluster at the coordinates captured in the image.

A Lot in a Name

Bennu takes its name from an ancient Egyptian deity connected to the Sun, creation, and rebirth, and its surface features are named for birds or bird-like creatures in mythology. Ryugu (or "Ryugo-jo") is a dragon palace in a Japanese fairy tale; the asteroid's feature names come from children's stories.

Puzzled, he pulled up the free software *Stellarium* and plugged in the coordinates. The background stars matched up, but there was no sign of the cluster's 20 or so pinpricks. After processing the image and others taken around the same time, he made a startling discovery: The "stars" had trails that all traced back to a single point on the asteroid's surface. These weren't stars — they were particles.

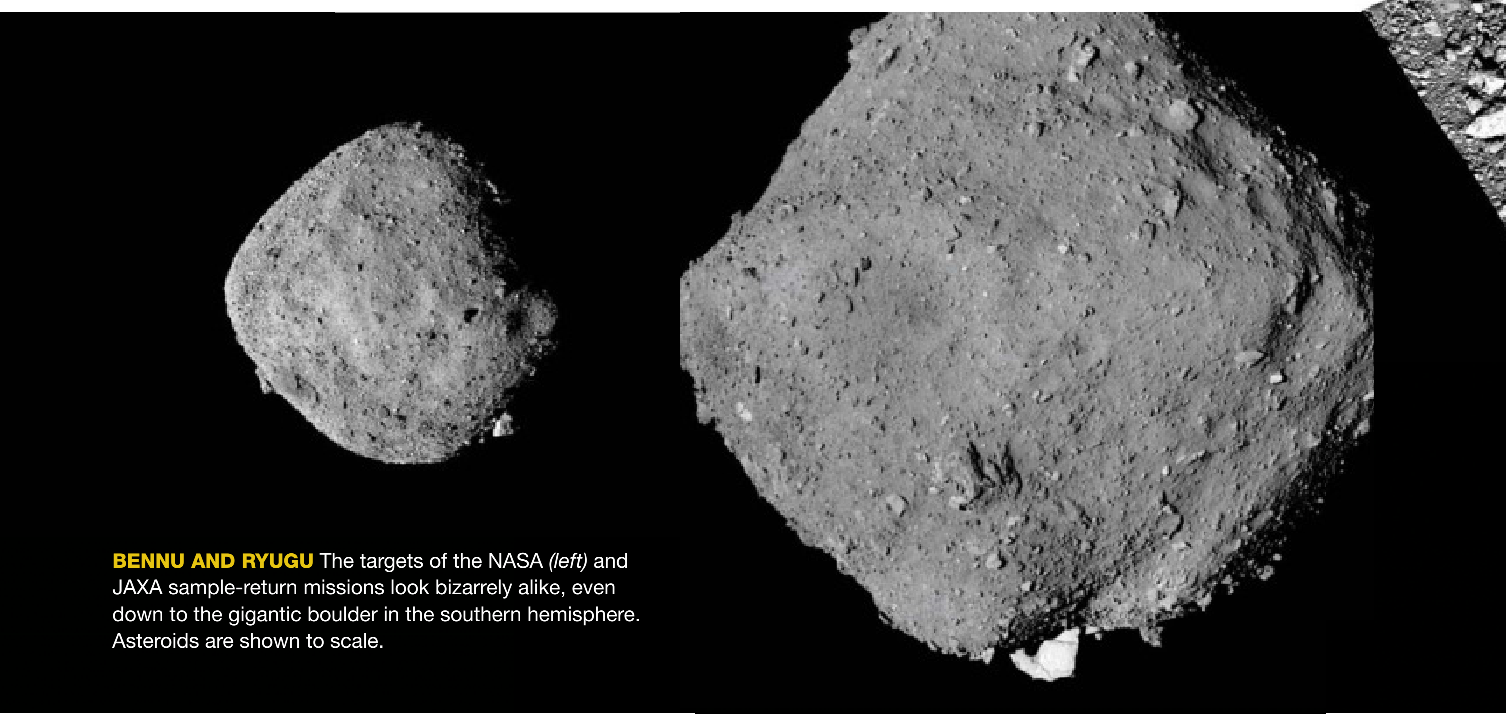
Bennu was firing rock bullets.

The particles put Hergenrother in a pickle. His presentation that morning was supposed to be about how OSIRIS-REX hadn't seen any signs of activity from the asteroid. This wasn't the moment to break the news to the whole team. So he hedged. Later, when everyone broke for lunch, he grabbed some of the mission leaders, including principal investigator (PI) Dante Lauretta (also University of Arizona), and showed them the images on his screen.

"Dante just kind of turned white," Hergenrother says. The PI's jaw dropped. "Here we are, we had just arrived at the asteroid, and the thing's shooting at us!"

Bennu's intermittent coughs of centimeter-size pebbles are one of several surprising results from OSIRIS-REX

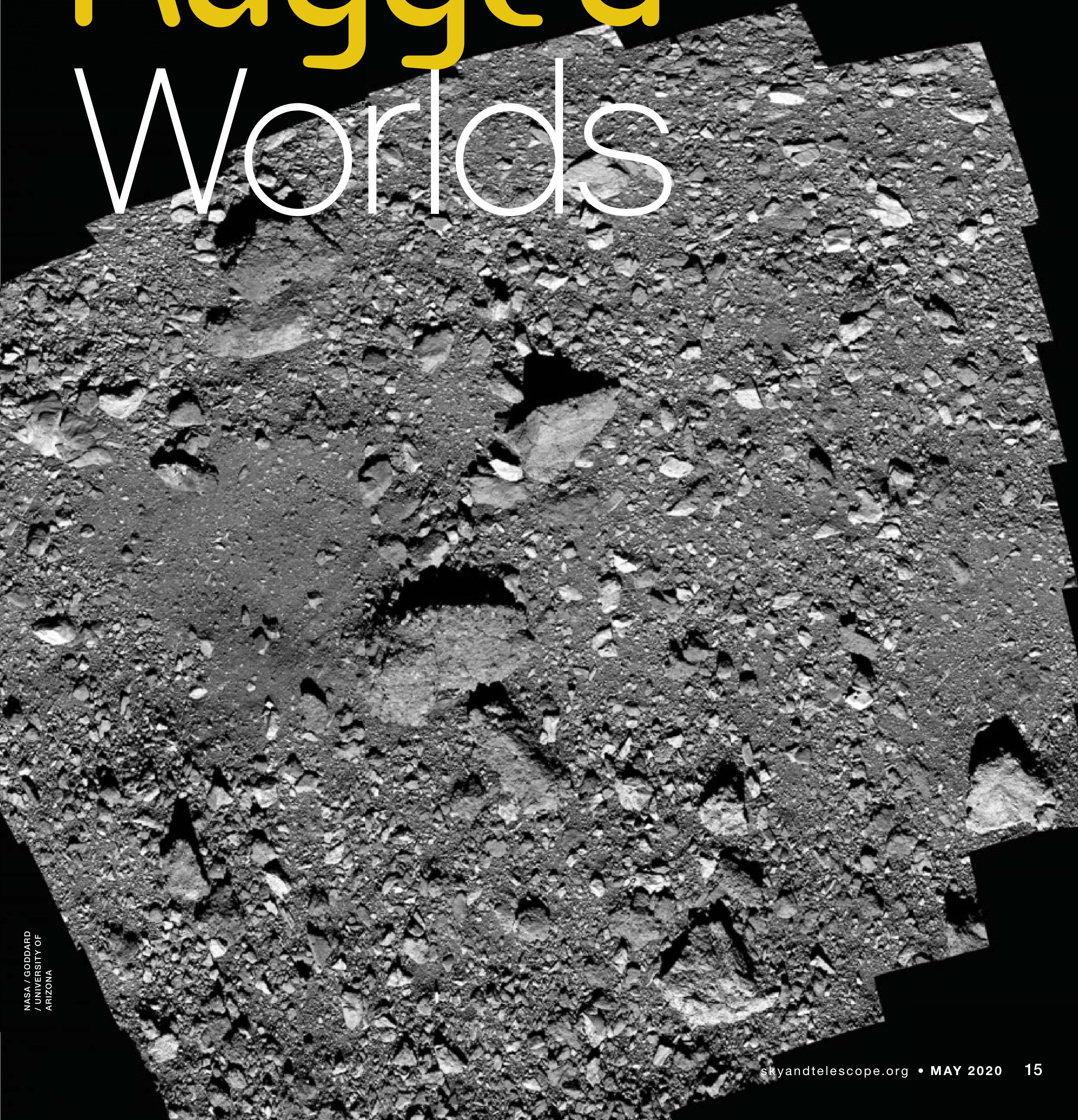
These unassuming space rocks are precious to planetary scientists, because they're time capsules.



BENNU AND RYUGU The targets of the NASA *(left)* and JAXA sample-return missions look bizarrely alike, even down to the gigantic boulder in the southern hemisphere. Asteroids are shown to scale.

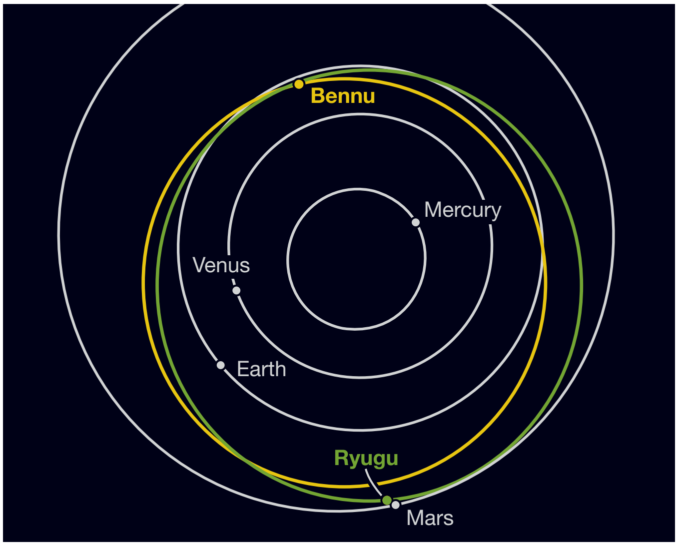
BENNU: NASA / GODDARD / UNIVERSITY OF ARIZONA; RYUGU: JAXA / UNIV. OF TOKYO / KOCHI UNIV. / RIKKYO UNIV. / NAGOYA UNIV. / CHIBA INST. OF TECHNOLOGY / MEIJI UNIV. / UNIV. OF AIZU / AIST

Rugged Worlds



NIGHTINGALE This 55-image mosaic shows the worn-looking crater on Bennu (center left) where OSIRIS-REX's primary sample site lies. The large boulder at center is about the size of a semi truck.

NASA / GODDARD / UNIVERSITY OF ARIZONA



▲ **NEAR-EARTH ASTEROIDS** Both Bennu and Ryugu cross Earth's orbit as they go around the Sun, making them *potentially hazardous asteroids*. The two have probably been in the inner solar system for several million years. Jupiter and Saturn's gravitational effects on the main belt drive asteroids inward, where they may survive for 10 million years or so before hitting something or being kicked out. Positions are for May 1st.

and its Japanese counterpart, Hayabusa 2, which recently left asteroid 162173 Ryugu after more than a year of exploration. Both projects are sample-return missions, designed to briefly touch down on the asteroids' surfaces, nab handfuls of debris, and bring the bits back to Earth for study (*S&T:* June 2018, p. 22). And both have revealed wondrously rubbly and perplexing worlds.

Formidable Terrain

Asteroids are not glamorous spacecraft targets. They don't have swirling cyclones like Jupiter or ancient, dried-up deltas like Mars. But these unassuming space rocks are precious to planetary scientists, because they're time capsules. Their chemical, structural, and geological makeups record a play-by-play of the solar system's early years. Therefore, in order to understand the origins of our planet and the compounds that make up our bodies, scientists turn to these chunks of planetary detritus.

Spacecraft have visited several asteroids, and we also have meteorites fallen to Earth that, based on their composition, we think come from different kinds of asteroids. We've even brought back samples from one: 25143 Itokawa, visited by the first Hayabusa spacecraft some 15 years ago. Itokawa proved a dead ringer for the most common type of stony meteorite, called *ordinary chondrites*.

But ordinary chondrites aren't the most pristine planetary crumbs out there. For that, we need *carbonaceous chondrites*. Scarce on Earth, these meteorites are the closest chemical matches to the Sun and look like the majority of the asteroids we observe. So to acquire the least tainted bits of the solar system's building blocks, scientists decided to snatch rocks from two carbonaceous asteroids whose orbits cross that of Earth: Ryugu and Bennu.

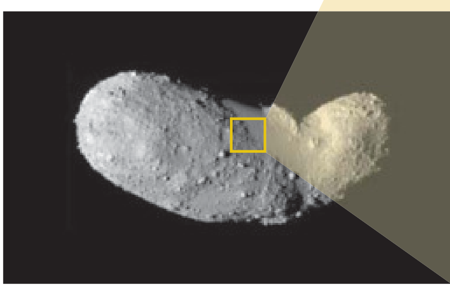
Small asteroids such as these — Bennu is about 500 meters wide, Ryugu 1 km — are rubble piles, conglomerations of debris from larger asteroids that broke up. Astronomers didn't know much about these two particular worlds when they picked them, only what they could infer from ground- and space-based telescopes. Because the surfaces of Ryugu and Bennu heat and cool quickly as they spin from daylight to darkness, scientists expected the two asteroids to have relatively smooth, beach-like regions like those found on Itokawa, and not to be covered in large rocks, which should take longer to warm and chill. OSIRIS-REX in particular was designed with a beach landscape in mind.

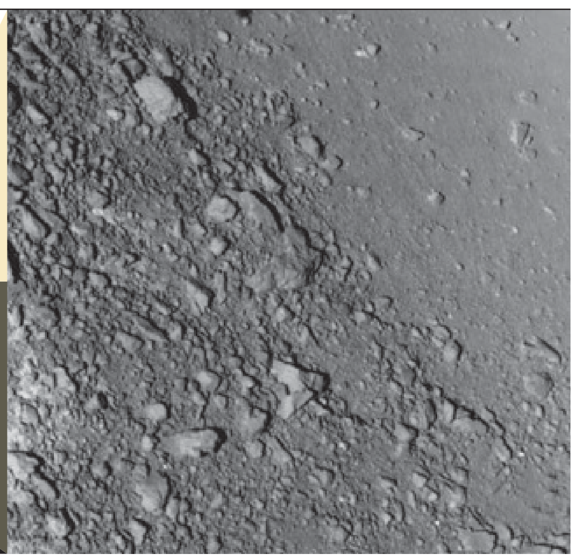
Nature had other ideas.

The spacecrafts' cameras revealed that both asteroids' surfaces are a sea of shards. Boulders ranging from about a meter to 100 meters wide dominate the landscape, with more big boulders near the poles than at the equator. It's as though someone took meteorites and strewed them everywhere — there's not a smooth region to be found. Upon seeing Bennu's surface, "My impression was 'Yikes! Where are we going to go on this asteroid?'" Lauretta said last September at a planetary science conference in Geneva, Switzerland.

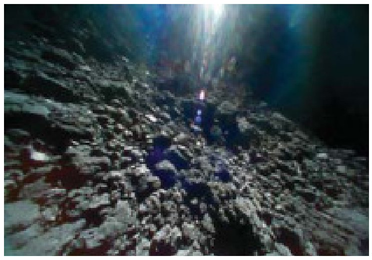
A range of rock types populates the asteroids, which are about as dark as fresh asphalt. Many rocks appear to be rubble piles themselves, mosaics of fragments fused together. There are boulders with a crumbly, cauliflower

▼▶ **ITOKAWA** *Below:* The target of the first Hayabusa mission, 25143 Itokawa is a near-Earth asteroid with few craters and patches of smooth-looking terrain. Its longest dimension is 540 meters, about the same size as Bennu. *Right:* This close-up shows the smooth region around part of Itokawa's neck. Most boulders shown are a few meters wide.





ORBITS: LEAH TISCIONE / S&T; ITOKAWA AND CLOSE-UP: JAXA



▶ **A BEACH OF ROCKS** Hayabusa 2 deployed two of its Minerva-II rovers to Ryugu's surface in September 2018. Rover-1B took these shots on September 23rd.

texture and others that look smooth and sharp-edged. Some are distinctly brighter than others. It's unclear how many of the differences are due to composition, as opposed to different degrees of exposure to space weathering and other processes.

Scientists on both teams suspect the rocks were able to masquerade as smoother surfaces when seen from afar because they're extremely porous — so porous that Hayabusa 2 scientists can't see the difference between Ryugu's fine-grained regolith and its boulders when they look at the surface in infrared, says the navigation cameras' science team leader Seiji Sugita (University of Tokyo). On both Ryugu and Bennu, the whole surface heats up at more or less the same rate. "That's the surprising discovery," he says. "We are really scratching our heads."

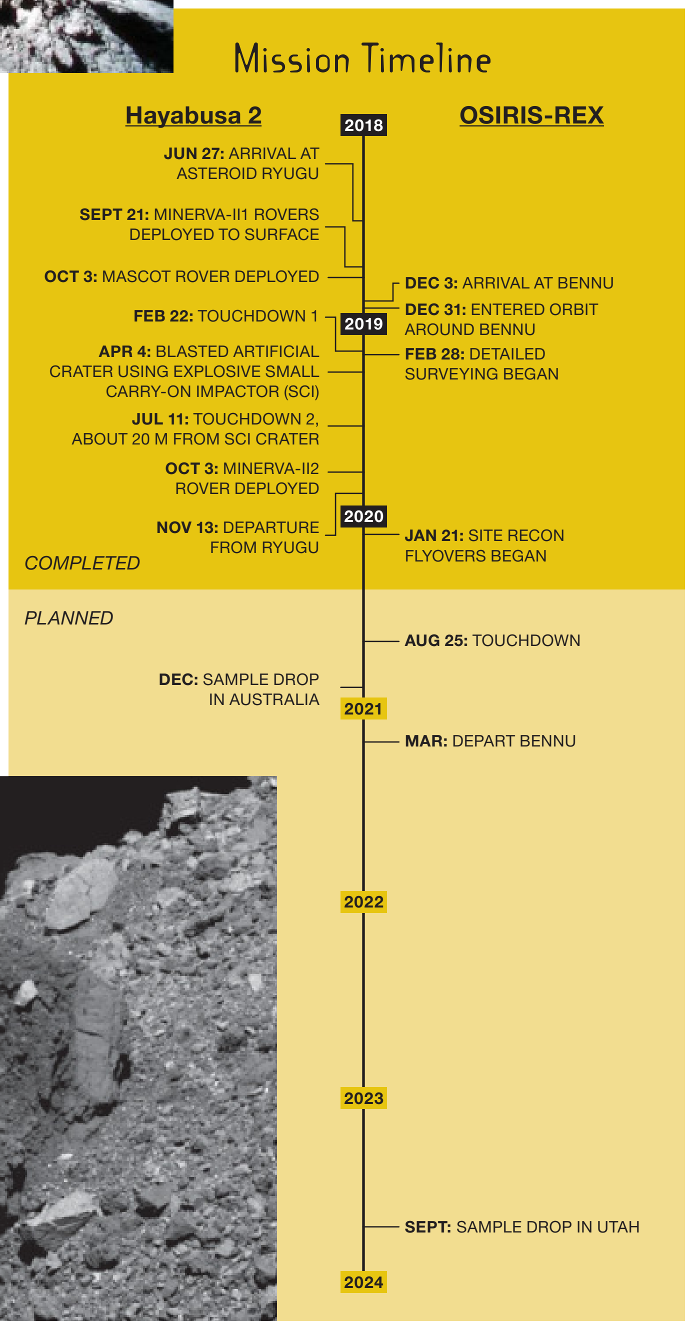
Another Hayabusa 2 experiment also suggests the asteroids are extraordinarily porous. Before its second and final touchdown on Ryugu, the spacecraft launched an explosive projectile to blast a hole in the surface, digging up material previously protected from space weathering. The scientists expected the resulting crater would be a few meters wide. Instead, the explosion dug a 13-meter-wide pit. Probably the rocks' low porosity, paired with the asteroid's weak gravity, explains the peculiarly large hole, mission manager Makoto Yoshikawa (Japan Aerospace Exploration Agency) said at the Geneva conference.

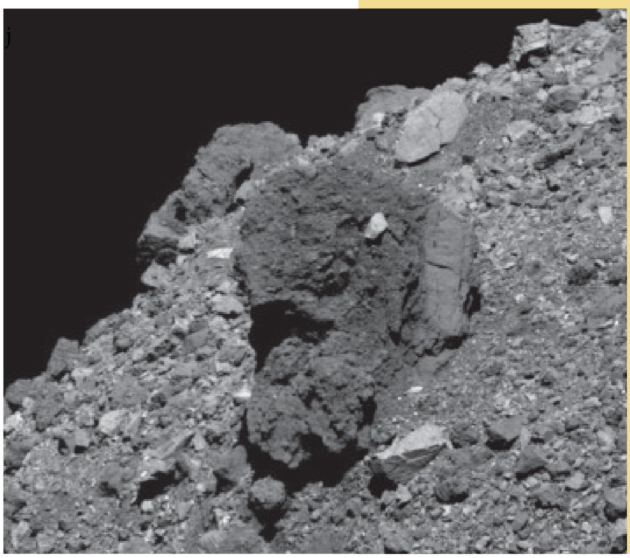
Hiding Their Ages (For Now)

Bennu and Ryugu are eerily similar. Both have the same diamond shape, the same density, same albedo. That's not what scientists expected: The two teams intended to go to different asteroids and then compare them. "When we got there, to Ryugu, we were like, 'Did, did we get to the right asteroid?'" Sugita jokes. "It was kind of a weird atmosphere."

Craters mottle both of the asteroids' surfaces, with large ones on the ridges that girth their equators. The pockmarks look soft-edged, not sharp like many on the Moon or Mars. Ryugu's big craters are about as densely packed as those on Bennu, but both appear to be short on craters smaller than 50 meters or so, implying something has erased them.

Such resurfacing might be connected to the strange die shape, Sugita suggests.





▶ **CAULIFLOWER** This strange, hummocky rock near Bennu's equator is one of the darkest boulders on the asteroid. The small, light-colored rock perched on it is 1.9 m (6.2 ft) long, about the size of a person. The backup touchdown site, called Osprey, lies directly behind the boulder from this perspective.

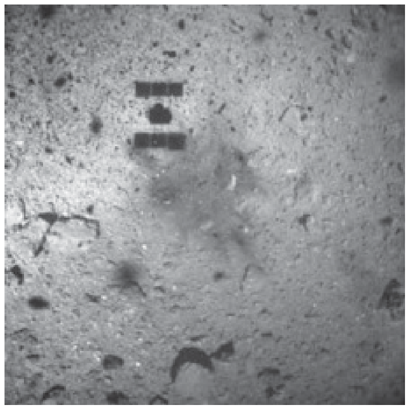
RYUGU'S SURFACE: JAXA (2); CAULIFLOWER ROCK: NASA / GODDARD / UNIVERSITY OF ARIZONA; MISSION TIMELINE: TERRI DUBÉ / *S&T*

> Bennu rotates every 4.3 hours, which means that every 4.3 hours its airless surface experiences a temperature rollercoaster.

Ryugu's equatorial ridge draws a symmetric circle around the asteroid's middle when viewed from above the poles, like a skirt whirled out by a rapid spin. The overall slope of the ground is also low and gentle, close to the critical angle for landslides if the asteroid had once been spinning about twice as fast as it is now, project scientist Seiichiro Watanabe (Nagoya University, Japan), Sugita, and their colleagues calculated last year. Perhaps Ryugu spun itself into its odd shape, generating landslides and erasing craters.

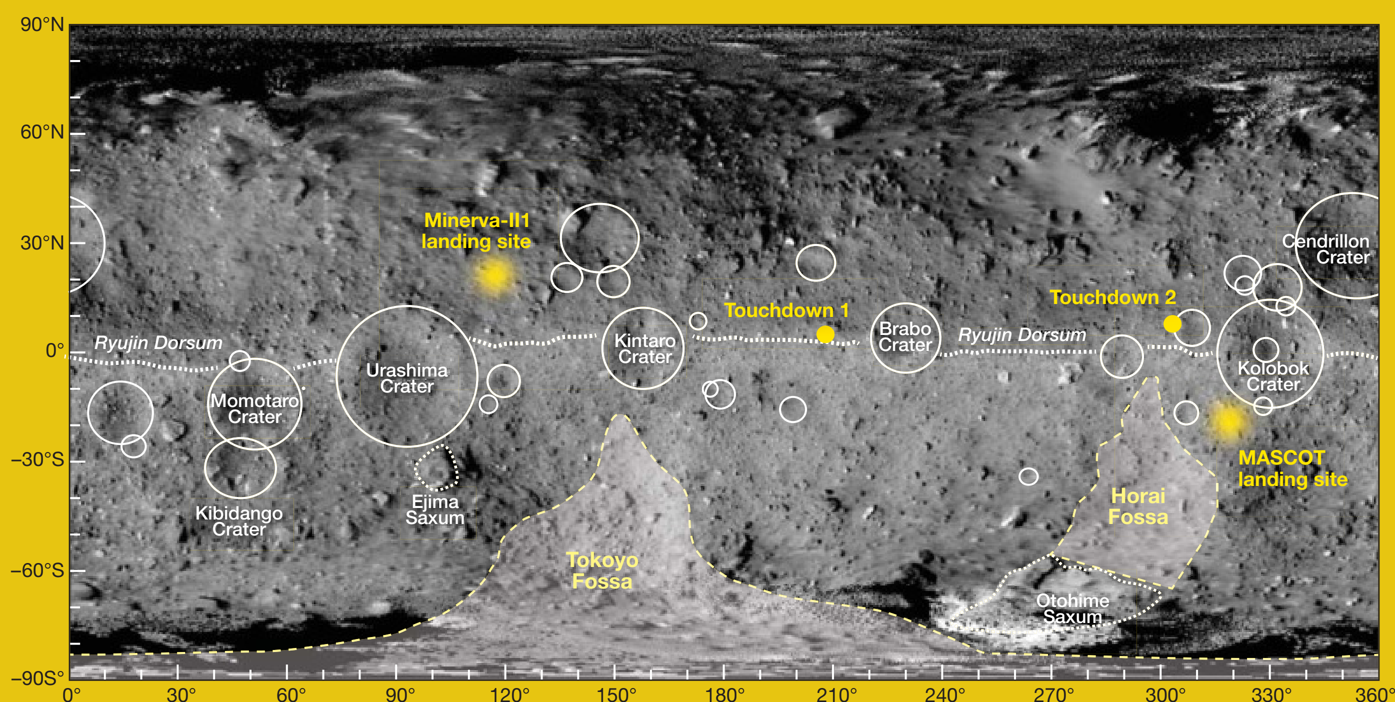
Lauretta is hesitant to favor a scenario for how the asteroids came by these shapes. At first, he was "fully onboard" with the rapid spin solution. But the large, ancient craters on the equatorial ridges give him pause. Those must have formed at least several million years ago, back when both worlds were still in the main asteroid belt between Mars and Jupiter and vulnerable to big crashes. That implies the ridges are old, perhaps even as old as the asteroids themselves. Simulations by Patrick Michel (Côte d'Azur Observatory, France) and others also indicate that a body built up from the shattered remains of an earlier asteroid can end up with a die shape, no landslides required.

That there are craters at all on Bennu and Ryugu "really shocked me," says asteroid scientist Bill Bottke (Southwest Research Institute, Boulder). Many small asteroids shed material, for various reasons. He thus expected the spacecrafts' targets to be essentially blank slates, wiped clean by all the goings-on. Perhaps it's easier to make craters on these bodies' surfaces than we thought, he says — a solution supported by Hayabusa 2's impact experiment. Or, he speculates, maybe asteroid surfaces don't erase themselves easily. That would imply that regions covered with large craters, such as the equatorial ridges, are ancient, whereas those with few small craters are young, such as ones near the poles.



◀ **LEFT A MARK** Hayabusa 2's shadow sails over the first touchdown site on February 22, 2019, just after completing the maneuver.

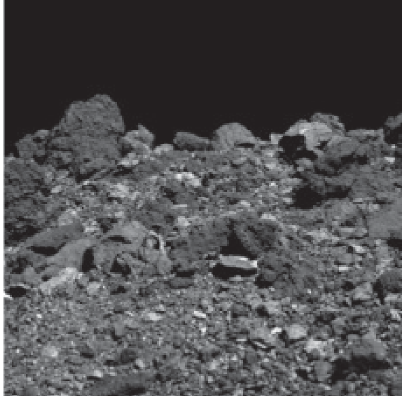
▼ **RYUGU** Hayabusa 2 dropped rovers at two known locations (yellow, hazy spots) on Ryugu, touched down twice, and mapped dozens of craters (white circles) as well as two large trenches, called *fossae*. The largest boulder, Otohime Saxum, appears stretched out here because of the severe projection distortions near the map's poles. The team has not yet identified where the final rover, Minerva-II2, landed.

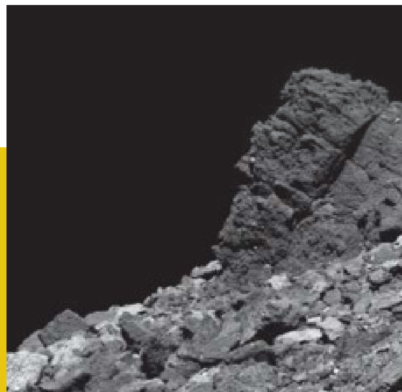


SHADOW OF HAYABUSA 2: JAXA / UNIV. OF TOKYO / KOCHI UNIV. / RIKKYO UNIV. / NAGOYA UNIV. / CHIBA INST. OF TECHNOLOGY / MEIJI UNIV. / UNIV. OF AIZU / AIST; SURFACE MAP OF RYUGU: JAXA AND S. SUGITA ET AL. / *SCIENCE* 2019

For now, scientists can't tell how old Bennu and Ryugu are. Both are near-Earth asteroids, strays that were kicked out of the main belt and into the inner solar system by the combined gravitational influences of Jupiter and Saturn. (This combined resonance also sculpts the inner edge of the asteroid belt.) Asteroids only survive in near-Earth orbits for about 10 million years before hitting a planet or the Sun, or being evicted from the system altogether. Based on where their orbits trace back to in the asteroid belt, Ryugu and Bennu are probably roughly a billion years old, Lauretta says.

The samples that OSIRIS-REX and Hayabusa 2 will bring home could tell us the little worlds' ages. The catastrophic impact that created the rubble the asteroids formed from would have reset certain chemical clocks, Lauretta explains. One useful clock is the ratio of potassium to argon. Potassium is a rock-loving element, incorporating itself into things like salts and feldspars. But it decays into argon, a noble gas — which doesn't like to bond with anything. Once the potassium atom decays, the now-argon atom will sit unhappily in the crystal structure until it receives the energy needed to kick it out. An impact can deliver that energy. The impact doesn't necessarily destroy the rock, he says, but it's enough to drive the argon out and reset the radioactive clock. From that point on, any argon in the rock dates back to the impact that made the pieces that formed the asteroid.





◀ **UP CLOSE** Shots of Bennu reveal an imposing surface replete with boulders. These rocks look deceptively small: The one in the top image's upper left is 14.5 m (48 ft) wide, the length of a boxcar; the little rock on the flat one in the middle image is the size of a horse; and the bottom image's boulder is as tall as a 747 aircraft's tail.

Water, Water Everywhere

One dramatic difference between Bennu and Ryugu is water. Prior spectroscopic observations had hinted that Ryugu's surface bore hydrated minerals, while Bennu looked relatively dry. Scientists found the reverse. Ryugu has much less water caught up in its rocks' crystalline structure than what's typically seen in a carbonaceous chondrite meteorite.

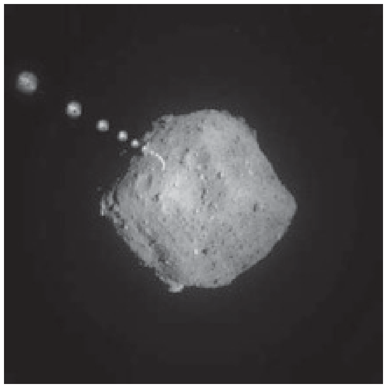
And Bennu? Bennu is practically soaked.

▼ **BENNU** The OSIRIS-REX team has chosen two potential landing sites on Bennu: Nightingale and Osprey. Also shown are the origins for the three largest particle ejection events (the Jan. 6 event launched from near the south pole). The various smaller ones come from all over the asteroid. The team hasn't assigned official feature names yet.

BENNU'S SURFACE: NASA / GODDARD / UNIVERSITY OF ARIZONA (3); SURFACE MAP OF BENNU: NASA / GODDARD / UNIVERSITY OF ARIZONA, D. S. LAURETTA ET AL. / *SCIENCE* 2019

"We saw this signal from *way* out, from thousands of kilometers away from the asteroid," Lauretta says — as soon as the team turned on the visible and infrared spectrometer, which detects water's absorption signal. Those data show that water has altered practically all the rocks that make up Bennu's surface. The rocks must be fragments from a large asteroid that had massive amounts of hot water percolating through it, altering its rocks, changing their chemistry, and building the clay minerals that dominate Bennu's surface today. "Think of a Yellowstone kind of environment," he says. "We went there to go find hydrated minerals — which generally are very rare in the solar system and in meteorites — and we got a whole asteroid full."

The difference between Ryugu and Bennu is puzzling because, based on the asteroids' orbits, scientists think the two worlds come from the same parent body. Perhaps something about the way in which the two rubble piles agglutinated affected how much water they held on to. Or perhaps Ryugu has been in the inner solar system much longer and been dried out by sunlight. Or maybe the asteroids aren't siblings after all.



◀ **TARGET PRACTICE** This continuous image sequence taken from an altitude of 1 km tracks a descending target marker, dropped on September 17, 2019, in preparation for the Minerva-II2 deployment on October 3rd.

Of all the discoveries so far, why Ryugu is so dry is the question Sugita most wants answered. "I think this really tells us what controls the water amount in the asteroid belt," he says. If scientists can determine why some asteroids retain water and others don't, it could help us understand how much water the planetary building blocks carried and why Earth and the other inner solar system planets formed with the amounts of water that they did. In 10 or 20 years, he predicts, we will look back on the discovery of Ryugu's dryness and say, "That moment, we learned something important."

▼ **ACTIVE ASTEROID** This enhanced, two-image composite shows some of the 93 particles observed launching from Bennu on January 19, 2019. The event was one of the three largest seen thus far.

Asteroid Spittle

And then there's Bennu's particle coughing fits. OSIRIS-REX has detected a few dozen outbursts, ranging from tiny explosions of 70 or more pebbles down to individual escapees. Many particles escape forever; others orbit for days before landing again. The sum effect is like a constant swarm of bees, Hergenrother says.

The Hayabusa 2 team can't tell whether Ryugu also spews shards — the spacecraft only darted close to Ryugu's surface to drop its rovers and take samples, and it also doesn't have as sensitive a camera. OSIRIS-REX, on the other hand, stayed within a couple of kilometers of Bennu's surface for months. No spacecraft has done that before. "It's very possible this happens on all asteroids, and it just hasn't been seen yet," Hergenrother says.

The team favors three possible causes for the ejections: the sublimation of water molecules liberated from minerals by grinding, cracking, and heating, which then propels grains off the surface; meteoroid impacts; and *thermal fracturing.*

Bennu rotates every 4.3 hours, which means that every 4.3 hours its airless surface experiences a temperature rollercoaster, plunging to 250 kelvin at night and surging to 400 K just after local noon. This dramatic cycling can cause rocks to crack and crumble — in fact, Hayabusa 2 images show that more than half of the cracks on Ryugu's surface line up north-south, as expected if the rocks cracked because they repeatedly rotate into darkness and light. Researchers see hints of a similar alignment on Bennu.

The three largest swarms of particles seen from Bennu thus far all launched during local afternoon. This makes sense if the cause is thermal fracturing, because it takes roughly three hours for heat to penetrate the rock's upper couple of centimeters, creating a difference in temperature that would stress the rock. But the other events happened at random times, even at night.

The range in timing suggests that more than one mecha-

TARGET DESCENT: JAXA / UNIV. OF TOKYO / KOCHI UNIV. / RIKKYO UNIV. / NAGOYA UNIV. / CHIBA INST. OF TECHNOLOGY / MEIJI UNIV. / UNIV. OF AIZU / AIST; SPEWING PARTICLES: NASA / GODDARD / UNIVERSITY OF ARIZONA / LOCKHEED MARTIN

▲ **TOUCHDOWN** Hayabusa 2 executed its second touchdown on July 11, 2019, near Ryugu's equator. The images capture 4 seconds before, the moment of, and 4 seconds after touchdown.

nism is at work, or perhaps they work together. Thermal stress could weaken the surface, "and then if a micrometeorite comes in and hits it, it's going to respond in a spectacular way," Lauretta speculates. If thermal fracturing is the root cause, then all near-Earth asteroids should be doing this, he adds. But if water is the key factor, then only Bennu and other hydrated asteroids will launch particles.

Since space agencies aren't likely to send a fleet of spacecraft to check dozens of near-Earth asteroids for this activity, the OSIRIS-REX team has found a clever alternative: The researchers partnered with SETI scientists to look for meteors that might be from Bennu's debris. So far, nothing. But after a couple of years, they hope to have enough observations to identify any potential links between meteor populations and near-Earth asteroids.

Landward, Ho

Hayabusa 2 has already finished its investigation of Ryugu, leaving the asteroid last November with two samples safely stowed. It will drop these in Australia during an Earth flyby at the end of 2020. With the extra propellant onboard, the spacecraft might continue on to whizz by another asteroid.

OSIRIS-REX, which arrived at its asteroid about five months after Hayabusa 2 did, intended from the beginning to take more of a tortoise pace with its sampling. But the jagged surface hasn't done the team any favors, either. The original plan to monitor the spacecraft's descent with lidar doesn't offer the guidance accuracy necessary to avoid potential hazards. Instead, the researchers will track features using a catalog they'll upload to the craft in advance.

OSIRIS-REX has a primary and a backup sample site, both announced in December 2019. The first, Nightingale, is a relatively smooth spot in a 70-meter-wide crater high in the northern hemisphere. Scientists think the crater and the debris it unearthed are fairly fresh. The backup site, dubbed Osprey, sits in a much smaller, equatorial crater surrounded by several types of rocks.

The spacecraft will do multiple recon passes of both sites in the first half of 2020 before touching down, hopefully in late August. It has until early 2021 to snatch its sample, then the craft will start the trip back to Earth. The cargo should drop in Utah in September 2023.

The retrieved rocks won't be in perfect condition. Both missions' grab-and-go strategies involve some rather violent jostling, and then there's the atmospheric entry. "It's coming in at 12.4 km/s, so it's going to shake up a bit on that ride," Lauretta says. "No getting around that. I tried."

Still, scientists expect to learn much from Hayabusa 2 and OSIRIS-REX's samples. The asteroid pieces, shaken up though they may be, will be treasures of chemical and geological insight, providing glimpses of how everything we see in the solar system — including the delightful array of carbon-based life around us — came to be.

■ Science Editor **CAMILLE M. CARLISLE** gasped when she first saw Ryugu's rugged landscape in a rover surface image.

Asteroid Prospecting?

Both scientists and starry-eyed entrepreneurs speak of mining asteroids for water and metals. But although these space rocks may someday provide valuable resources, we have a long way to go before that day comes. "We're talking about the space economy of the 22nd century," says asteroid expert Richard Binzel (MIT).

Water will likely be the first resource utilized, he says. But first we have to learn how to recognize which asteroids have minable water — something that, given the surprise of a wet Bennu and dry Ryugu, we clearly need to work on. The samples OSIRIS-REX and Hayabusa 2 bring back will tell us how much water the asteroids' minerals contain and potentially indicate how much future spacefarers could extract globally.

"But I don't predict it for this century," Binzel says. "I would love to be wrong."

JAXA (3)