POSSIBLE PHOTOS

- An IDP (a fragile-looking one)
- Brownleeite TEM photo
- Comet 26P/Grigg-Skjellerup (pretty sky photo; can do any comet if this specific one is too hard)
- Comparison of some small world surfaces at same scales? Itokawa, 67P, Eros?
- JSC sample curation facility (ideally, Keiko in her lab)
- Hayabusa2 and OSIRIS-REx art

[caption]
Some IDPs are fragile, have primitive properties, and do not appear to be related to any meteorite. IDPs probably come from collisions among asteroids and from comet jets, but where any specific particle came from is unknown.

Keiko Nakamura-Messenger *is a mission research scientist in the Astromaterials Research and Exploration Science Directorate at NASA's Johnson Space Center.*

Precious Dust

Two Missions Converge on Asteroid Sample Returns

Far-flung spacecraft deliver incredible views of distant worlds. But there's nothing like bringing samples back to Earth. Instruments carried by spacecraft have limitations—of power, complexity, size, and number. Their investigations leave many fundamental questions unanswered, questions that we might be able to answer if only we had samples.

This summer marks the beginning of an exciting new era in sample-return missions: NASA's *OSIRIS-REx* spacecraft arrives at asteroid Bennu, and the Japanese *Hayabusa2* spacecraft arrives at asteroid Ryugu. Both are primitive asteroids—dark remnants of Solar System formation that carry carbon and water—a type of asteroid that's never been visited before. After thoroughly mapping their respective asteroids for geology and mineralogy, each probe will collect surface samples and return them to Earth. I can't wait to study them in my laboratory.

Cosmic-dust pioneer Kazu Tomeoka introduced me to the dream of sample-return missions 20 years ago. In those days, the only returned extraterrestrial samples were from the Moon. He said to his students, "In the near future, we will be able to collect samples from asteroids and comets. There will be no need to wait for meteorites or cosmic dust to come and fall from the sky. And some of you might be the first to look at those samples." This inspired my life's work: laboratory analysis of returned astromaterials.

EARLY EFFORTS

Returned astromaterials are not the only extraterrestrial samples we can study. Meteorites and cosmic dust have been collected by scientists at clean locations on the surface of Earth (such as Antarctica), by airplanes in the upper atmosphere, and by satellites in low Earth orbit. Interplanetary dust particles (IDPs) were first collected in the upper stratosphere by high-altitude balloon flights, and NASA now routinely collects IDPs with high-altitude aircraft.

Scientists would like to link cosmic dust and meteorites with their parent asteroids or comets. To do that, scientists have dispatched high-altitude flights timed to sample meteor showers from known comets and asteroids whose orbits pass near Earth's. Scientists have connected some meteorites to certain classes of asteroids or comets based on composition, spectral properties (color), or orbits (inferred from observing the path of their parent fireball in the atmosphere). But these inferences are uncertain and controversial.

Studies of meteorites and cosmic dust built a strong foundation for sample-return missions, by revealing the early history of the Solar System and pushing the development of ever more capable instrumentation. But this type of study is compromised by the uncertain origins of found specimens and effects of terrestrial weathering and contamination. As instruments have become more sensitive and we examine materials at finer scales, these effects have become bigger problems. Our progress is especially relevant to studies of organic matter, which is ubiquitous in the Solar System.

NEW TECHNOLOGIES, NEW INSIGHTS

Professor Tomeoka was among the first scientists to examine IDPs using transmission electron microscopy (TEM). With TEM, he saw component crystals at the atomic scale. Tiny dust particles became immense landscapes that record the origins of their parent bodies.

I followed my mentor's path to study IDPs and meteorites using electron microscopy. While investigating an IDP collected during the April 2003 Pi Puppid meteor shower (associated with comet 26P/Grigg-Skjellerup), I discovered a new mineral, with the chemical formula Mn_1Si_1 (mono-manganese silicide). We named the mineral Brownleeite, after Donald Brownlee, the pioneer of cosmic dust collection. Identified in a single grain comprising just a few thousand atoms, it was the smallest mineral ever approved by the International Mineralogical Association. Studying its possible origins, we obtained data that gave us clues to how Brownleeite forms. And though we'd like to think the Brownleeite came from comet 26P/Grigg-Skjellerup, we can't be sure.

Brownlee was the principal investigator of NASA's *Stardust* mission, which returned the first direct samples of a comet. *Stardust* flew by comet 81P/Wild 2, beyond the orbit of Mars, and captured particles streaming from the comet's surface. The spacecraft returned to Earth in January 2006. The *Stardust* samples from Wild 2 provided surprises about the nature of early Solar System materials, including "refractory" minerals that formed in high-temperature environments near the Sun. This unexpected discovery—made possible by the opportunity to study samples brought directly from the comet—showed that the cold, distant regions where comets formed were not isolated refuges of interstellar materials. Instead, comets formed from *mixed* materials, many of which came from the heart of the Solar System.

We have learned from fruitful experience with *Apollo* specimens that more discoveries are yet to come. Developments in technology have added capabilites to laboratory instruments and enabled new studies that were inconceivable when *Apollo* astronauts returned lunar samples a half-century ago. At the same time, materials once thought to be contaminants, such as organic matter in astromaterials, are now understood to be significant constituents. [TINY GRAINS SIDEBAR ABOUT HERE]

Sample-return missions make it possible to solve the mysteries of how the Solar System's primordial organic matter formed in space and evolved within asteroids and comets. By collecting material directly from primitive bodies in a well-studied geological context, and keeping them uncontaminated all the way from space into the laboratory, we can eliminate the most vexing sources of uncertainty. We plan missions carefully and track all possible sources of contamination or sample alteration, from spacecraft assembly and launch through the recovery of the sample-return capsule. At NASA, we begin planning how we will curate samples at the very beginning of the mission. This approach ensures that archived samples remain pristine for future generations, which will certainly wield even more advanced analytical technologies.

BEST OF BOTH WORLDS

Today I work on two asteroid missions: JAXA's *Hayabusa2*, built by my mother country Japan, and NASA's *OSIRIS-REx*, built by my adopted country, the United States. Both spacecraft approach their target asteroids this summer. JAXA and NASA have agreed to exchange portions of the samples they will return, and the science teams are actively collaborating. Several Japanese scientists will join *OSIRIS-REx* mission operations in Tucson, Arizona, and there are NASA-funded scientists on *Hayabusa2*. The collaboration between these missions will benefit both.

Hayabusa2 will obtain the first of three planned samples from asteroid Ryugu in October 2018. It will descend, briefly touch the surface with a sampler, and collect regolith loosened by a small projectile. This touch-and-go sampling operation presents the mission's most significant risk. (*Hayabusa2*'s predecessor, *Hayabusa*, was damaged during its sample collection attempts and almost did not recover.)

Hayabusa2 carries a couple of landers that will study the asteroid's surface. *Hayabusa2*'s data on asteroid surface properties will be valuable for *OSIRIS-REx*, even though that mission has targeted a different asteroid. Since nobody has ever visited the surface of a primitive asteroid, the structure of the surface of this type of body is unknown. Everything we learn at Ryugu has the potential to help us at Bennu.

As the Sample Site Scientist for *OSIRIS-REx*, I am leading the effort to identify the most scientifically valuable sites on asteroid Bennu using data we will obtain as the spacecraft gets closer to its target. One early effort will focus on developing a 3D shape model that will be crucial for precise navigation around the asteroid. The *OSIRIS-REx* team is sharing expertise and software with the *Hayabusa2* team to aid them in making their own 3D model and navigation plans. These collaborations make both missions stronger and safer. As a NASA employee who is Japanese deep inside of my heart, I am particularly grateful to see these two missions, which could otherwise be rivals, working together toward mutual success.

THE WAY WE EXPLORE IN THE FUTURE

I am honored to be the curator of NASA's portion of the Ryugu sample to be returned by *Hayabusa2*, and the deputy curator for the *OSIRIS-REx* sample. At Johnson Space Center, we will document, protect, and prepare samples for analysis by qualified scientists all over the world. This will take place inside the same building where all of NASA's returned extraterrestrial materials have been curated since the *Apollo* missions.

Hayabusa2 and *OSIRIS-REx* scientists are developing plans for sample analyses that will maximize science results from these missions. Ryugu and Bennu are both thought to be carbonaceous and water-rich asteroids. In terms of quantity, *Hayabusa2* will return less than *OSIRIS-REx*, but it will sample three different locations. *OSIRIS-REx* will obtain a more massive sample from a single site. In these two missions, combining different sampling strategies, we have an unprecedented opportunity to study the most pristine, least-altered asteroid materials and their geological processes.

Sample-return missions like *Hayabusa2* and *OSIRIS-REx* are laying the groundwork for future exploration of the Solar System. Analyses of returned samples can provide detailed understanding of the environmental hazards for astronauts and spacecraft as well as previews of resources and models for how to extract those resources. Prospecting precedes mining on Earth, and sample return is the prospecting that will precede mining in space.

We owe an enormous debt to the pioneers of astromaterial sampling—those who collected from the deep sea, Antarctica, the stratosphere, the Moon, comet Wild 2, and more. Thousands of engineers and scientists worked to make those discoveries happen. Thousands more are working today on new missions. Sample return pays enormous dividends, and once samples are back to Earth, they can be studied by our children and their children, regardless of their nationality, with the best instruments that the future will offer.

[LONGER AUTHOR BIO. Add link to asteroidmission.org, OSIRIS-REx social media, and Hayabusa2 website.]

[sidebar]

Astromaterials in Tiny Grains

A good example of our new understanding of astromaterial chemistry is the presolar organic nanoglobule. Organic globules are round, often hollow, carbonaceous grains less than a micrometer in diameter (a human hair is typically 60 to 100 micrometers in diameter). They occur in almost every primitive astromaterial sample. These tiny grains used to be viewed as probable contaminants because meteorites are usually collected from dirty locations or many years after their fall.

I was extremely fortunate to be able to study a primitive meteorite that was quickly recovered after landing on a frozen lake in British Columbia during the dead of winter. It was about as pristine as a sample collected on Earth can get. In this Tagish Lake meteorite, I could see hundreds of organic nanoglobules, looking just like the "empty Easter eggs" we saw all over TEM images of samples thought to be less pristine.

Even so, there was skepticism that the globules were truly extraterrestrial. The proof of their origins was made possible with a new instrument, the NanoSIMS. With coordinated isotopic measurements, we showed that organic globules carry isotopic anomalies characteristic of certain photochemical processes, which would take place in cold molecular clouds in deep space or in the outermost regions of the protosolar disk. This finding is significant for both astrochemistry and astrobiology, because it suggests primitive meteorites and cometary dust particles delivered organic precursors to the early Earth—and to other planets and satellites as well. Organic nanoglobules have now been reported in almost every primitive astromaterial sample.

[sidebar]

Where We Study Returned Samples

In total, we have 380 kilograms (more than 800 pounds) of extraterrestrial rocks, including specimens from all six *Apollo* landings, more than 10,000 meteorites collected by United States expeditions to Antarctica, samples of cosmic dust, and samples from *Stardust*, *Genesis*, and *Hayabusa*. Each collection has unique clean room requirements.

At Johnson Space Center, the dedicated *Hayabusa2* sample clean room design is now complete and will soon begin construction next to our *OSIRIS-REx* facility. NASA is now evaluating proposals to return samples from Mars, a comet's surface, or Enceladus.

As analysis techniques improve, the required sample sizes become smaller. We have been developing new techniques for processing tiny astromaterial samples inside a specially designed "glovebox," which will minimize the prospect of Earth life contaminating future returned samples.