The Past, Present, and Future of Extraterrestrial Sample Return

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Teaser: Retrieving samples from distant solar system bodies has revolutionized our understanding of the cosmos and our place within it.

When poet William Blake wrote of seeing a world in a grain of sand, proposing the idea that even a speck of rock could hold clues to the cosmos, he may not have envisioned that humans would one day hold fragments of distant worlds in a literal sense. Yet today, more than 2 centuries after Blake wrote "Auguries of Innocence" and more than 5 decades since rocks were first returned from beyond Earth, that is a reality.

Precious rocks have been retrieved from the Moon and multiple asteroids, dust has been harvested from a comet's tail, and we have even captured "wind" from the Sun. In the next decade, not only will humanity make a long-awaited return to the Moon, but also plans are in progress for spacecraft to collect rocks from Mars and its moon Phobos.

The earliest sample return missions were crewed by people who manually collected samples from the Moon, but more recently, humans have ceded the job to spacecraft and rovers carrying complex sampler mechanisms. These remotely operated robotic missions can boldly go where humans cannot. They provide direct access to samples that allow us to answer long-standing questions about the geological and chemical histories of varied celestial bodies, from the Sun and the Moon to asteroids and planets. Extraterrestrial samples also offer insights into the habitability of planetary bodies and help us to understand how Earth evolved to be the only apparent life-supporting body in our solar system. And they aid in predicting and mitigating potential threats from cosmic bodies such as near-Earth objects.

The detail with which returned samples can be studied using a variety of sophisticated analytical instrumentation in laboratories on Earth is simply not possible in space. Technical limitations and size constraints of spacecraft and the high costs of space travel make such efforts impractical. The crucial need to keep collecting, returning, and preserving material from beyond our own planet is thus likely to continue the legacy of past sample return endeavors well into the future.

From Telescopes to the Moon

Fascination with the night sky and the realms beyond Earth is no recent interest for humanity. Going back millennia, even early civilizations tracked and recorded the movements of the heavens to understand our origins and significance. Extraterrestrial sample return is a comparatively young endeavor, with the first samples returned by NASA's Apollo 11 mission in 1969.

So it stands to reason that most of what we know about our solar system and our place within it stems from remote observations, made first with the naked eye, then with telescopes, and later by myriad spacecraft missions. Yet sample retrievals from distant bodies have revolutionized our understanding of the cosmos and our place within it.

[Embed 1: Moon sample collage]

No celestial body is a better example of the revolutionary power of sample return than the Moon. Prior to the Moon landings, our understanding of Earth's nearest neighbor was limited to what could be inferred from afar. We learned, for example, that the Earth-Moon system has high angular momentum, that the Moon has a very different spin axis orientation than Earth, and that the Moon is not in Earth's plane of rotation.

All of these observations pointed to something being flawed in our ideas about the Earth-Moon relationship, but we did not know why, and there was no consensus as to how the Moon formed. Prior to Apollo 11, the front-runner hypotheses to explain the Moon's origin included ideas that Earth and the Moon accreted simultaneously from early solar system materials, that early Earth rotated so fast that it threw off a portion of itself that became the Moon, or that the Moon formed elsewhere and was eventually captured by Earth's gravity. With the first return of Moon rocks, scientists rapidly acquired new lunar geochemical and geophysical data that revolutionized our understanding of the Moon and promptly debunked each of those hypotheses.

The results of those early analyses of lunar rocks, rather than proving confounding, were incredibly exciting. Scientists were forced to rethink what they thought they knew about the Moon. They eventually formulated the explanation that is broadly accepted by the scientific community: the Giant Impact Hypothesis. This hypothesis posits that the Moon formed from the remnants of an impact between a young Earth and another body, known as Theia, which was likely about the size of modern-day Mars [*Hartmann and Davis*, 1975]. This hypothesis not only filled in how our own Moon formed, but also helped us understand the chaotic early history of our solar system and how planetary bodies evolve.

The moral of the story is that the results of detailed, laboratory-based sample analyses can contradict interpretations made from remote observations alone. That is because remote observations, like those collected from orbit around a planetary body, provide data at different scales—ranging from centimeters to hundreds of meters or more—compared with data from physical samples, which can provide information at finer scales, from centimeters down to the atomic scale. These different ranges of scale suggest that the two approaches can be used synergistically, each informing the other, rather than that sample analysis should replace remote observations.

Meteorites Versus More Fragile Materials

The return of rocks that were incontrovertibly from the Moon led to another exciting discovery: Lunar meteorites had long been present on Earth's surface, hiding in plain sight. We simply did not know what a lunar meteorite should look like until we had pieces of the Moon for comparison. Thus, returned samples also provide context for studying and understanding meteorites.

In addition to lunar meteorites, we also already have access to rocks that arrived from Mars, the asteroid belt, and possibly other worlds. These meteorites have offered valuable, but hardly complete, glimpses of the bodies from which they originated.

Spacecraft can safely return other extraterrestrial samples that can help expand our knowledge of these bodies but that would not survive an unprotected journey through Earth's atmosphere. The Japan Aerospace Exploration Agency's (JAXA) Hayabusa 2 and NASA's OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer) missions, for example, brought back samples of fragile carbonaceous asteroid debris.

[Embed 2: Asteroid sample collage]

If similar materials came to Earth as meteorites, it's unlikely they would survive atmospheric entry—and even if they did, they would rapidly degrade at Earth's surface through interaction with water in the air [*Yokoyama et al.*, 2022]. The asteroids sampled by these missions are cosmic time capsules representing some of the earliest solar system materials, which have remained unchanged for the past 4.5 billion years and are unaltered by residence on Earth. That continuity with the distant past is incredibly important in the search for clues to the origin of life.

Similarly, the friable (crumbly) nature of the sedimentary rocks that make up so much of Mars's surface means it is highly unlikely, if not impossible, that they would survive ejection from the planet, the journey through space, and entry through Earth's thick atmosphere. Indeed, all but one known Martian meteorite is igneous—they originated from magmas—and decades of investigations based on data from orbiting spacecraft and from rovers have shown that these meteorites are not broadly representative of the Martian crust [*Udry et al.*, 2020]. Rather, Martian meteorites represent only small slices of Mars's lengthy history. Further, we do not know the specific locations from which Martian meteorites (or any meteorites, for that matter) were ejected—they lack geologic context.

To understand Mars's history and evolution more fully, we must collect samples directly from its surface. The Mars 2020 Perseverance rover has called Jezero crater in the planet's northern hemisphere home since 2021. Perseverance has so far cached 23 samples, including 12 of sedimentary rocks and soil that would not survive the journey to Earth as meteorites. Those samples are nominally expected to be brought to Earth in the next 2 decades by the ongoing Mars Sample Return (MSR) program, a joint initiative between NASA, the European Space Agency, and other partners. China's Tianwen-3 mission, projected to launch in 2030, will also attempt to retrieve samples from Mars.

Like the Grand Canyon does on Earth, Jezero crater exposes rocks representing much of Mars's geologic history, and the cached samples have been carefully curated to sample a larger window of that history than available meteorites do. These samples will provide invaluable insights into water-driven processes on the Red Planet, and they might reveal potential biosignatures of past life and help us understand how Mars became the dusty, desolate planet we know today [*Beaty et al.*, 2019].

The Lasting Value of Bringing the Solar System Home

Samples returned from space and kept in their original state are gifts that keep on giving. In the half century since NASA's Apollo and the Soviet Union's Luna missions captured imaginations around the world, samples from those programs have continued to yield insights. Today a generation of scientists (including us) who were not born at the time of those missions are applying cutting-edge technology to those same samples to address questions not dreamed of during the Apollo era: Can we place Apollo samples into a lava stratigraphy without cutting them open? What are the origins of lunar water? Can we detect solar wind–derived hydrogen and helium in lunar soils? [e.g., *Wilbur et al.*, 2023].

[Embed 3: Sun sample collage]

Over the same time span, the realm of space exploration has of course expanded significantly, in both the array of celestial bodies explored and the diversity of people working on these endeavors. Robotic missions have returned samples of solar wind particles (NASA's Genesis mission), cometary dust (NASA's Stardust mission), and asteroid samples (JAXA's Hayabusa and Hayabusa2 and NASA's OSIRIS-REx missions), as well as previously unsampled Moon rocks (China's Chang'e-5 mission). As with the Moon missions, scientists will no doubt continue studying these samples for decades to come.

In the coming decade, NASA's Artemis program will return humans to the Moon to explore and take samples for the first time since the Apollo 17 astronauts left the lunar Taurus-Littrow highlands in December 1972. And China's robotic Chang'e-6 mission will set its sights on returning the first soil and rock samples from the farside of the Moon.

NASA is also exploring options for robotic sample return from the Moon, including with the Endurance mission concept for a rover that would collect samples across the farside and deliver them to Artemis astronauts. These missions are stepping stones to further explore and return samples from Mars (MSR and China's Tianwen-3 mission) and one of its moons, Phobos (JAXA's Martian Moons Exploration, or MMX, mission) [*Usui et al.*, 2020].

[Embed 4: Comet sample collage]

Beyond the near term, mission concepts are being developed to return samples from more exotic locales, including the icy surfaces of a comet and of the dwarf planet Ceres, endeavors that will be decades in the making and will require substantial technological development. The goal to return icy samples may be lofty, but the payoff could be paradigm shifting.

Comets contain material left over from the birth of the solar system that has remained unchanged since then, effectively frozen in time, thanks to those bodies' substantial distance from the Sun. Access to cometary surface samples would provide unparalleled insights into the primordial nature of bioessential elements and water. In particular, such samples could shed light on how organic molecules evolved into life and where Earth's vast volumes of water came from.

From Inconceivable to Inspiration

Sample return missions are driven by scientific inquiry. Beyond sating intellectual curiosity about our celestial surroundings, however, these missions benefit society in other ways. Their technical development can advance technologies useful for applications outside space exploration. For example, advances made during the Apollo program paved the way for modern fireproof materials, water treatment systems, and even footwear.

Moreover, sample return missions aid in planetary defense efforts intended to predict and mitigate impacts of potentially dangerous asteroids and comets. Knowing what such bodies are made of and how strongly or weakly they are consolidated gives us a better idea of how to deflect or disrupt them.

These missions' inherent difficulty and the shared spirit of exploration they embody can capture public imagination and inspire younger generations to pursue STEAM (science, technology, engineering, arts, and mathematics) careers. Because they benefit from involvement of large, diverse teams representing myriad areas of expertise—from science and engineering to art, media, and education—and different cultures and countries, they can also foster international collaboration and build cross-cultural dialogue and respect.

It was once inconceivable that we could travel to another celestial body and bring pieces back. Even now, some places may seem out of reach for sample returns—Venus, Jupiter's moon Europa, and Saturn's moon Enceladus, to name a few. But considering humanity's unrelenting perseverance, we can reasonably hope that future generations will eventually have fragments of these distant worlds to admire and study. Such is the dream and legacy of extraterrestrial sample return.

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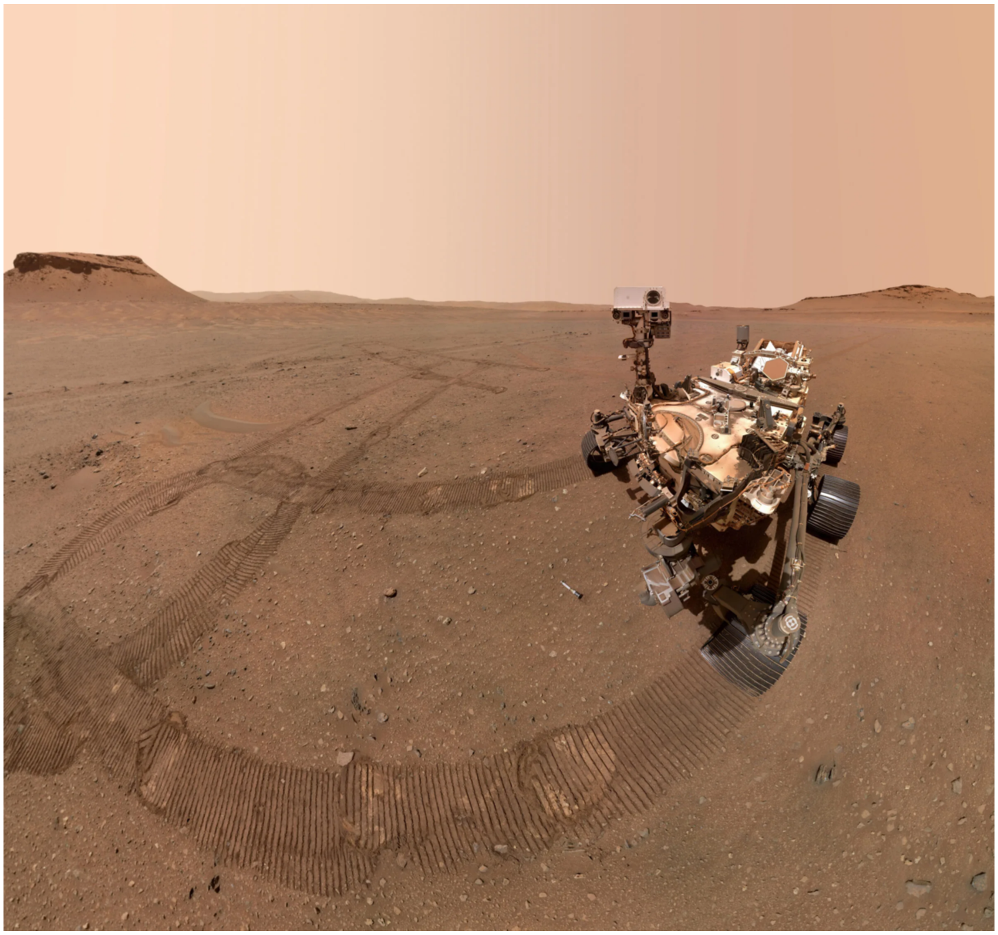
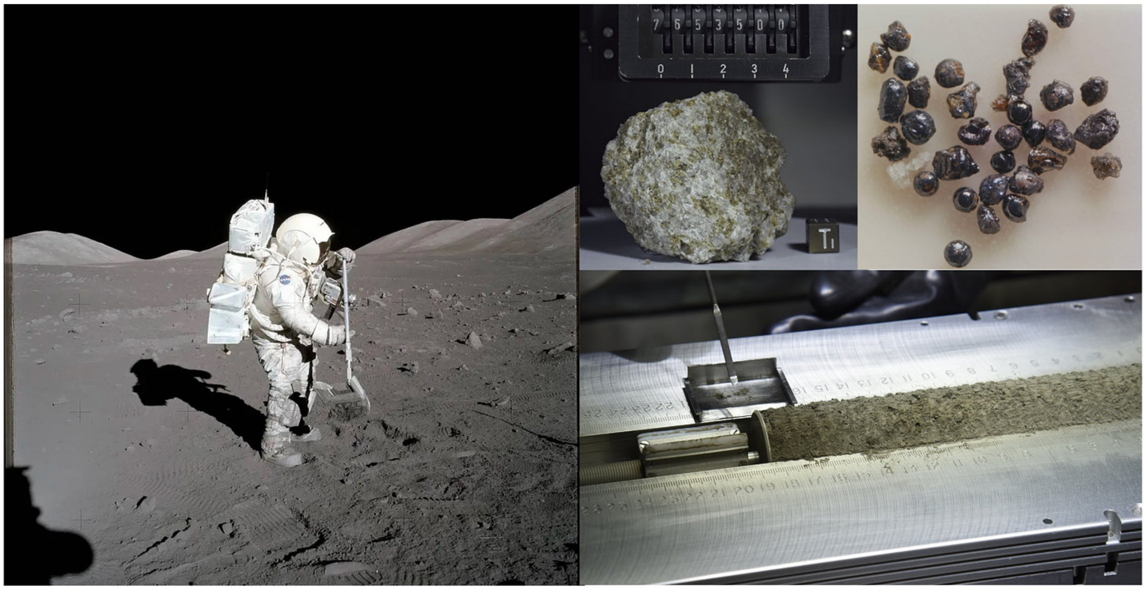
Image Information

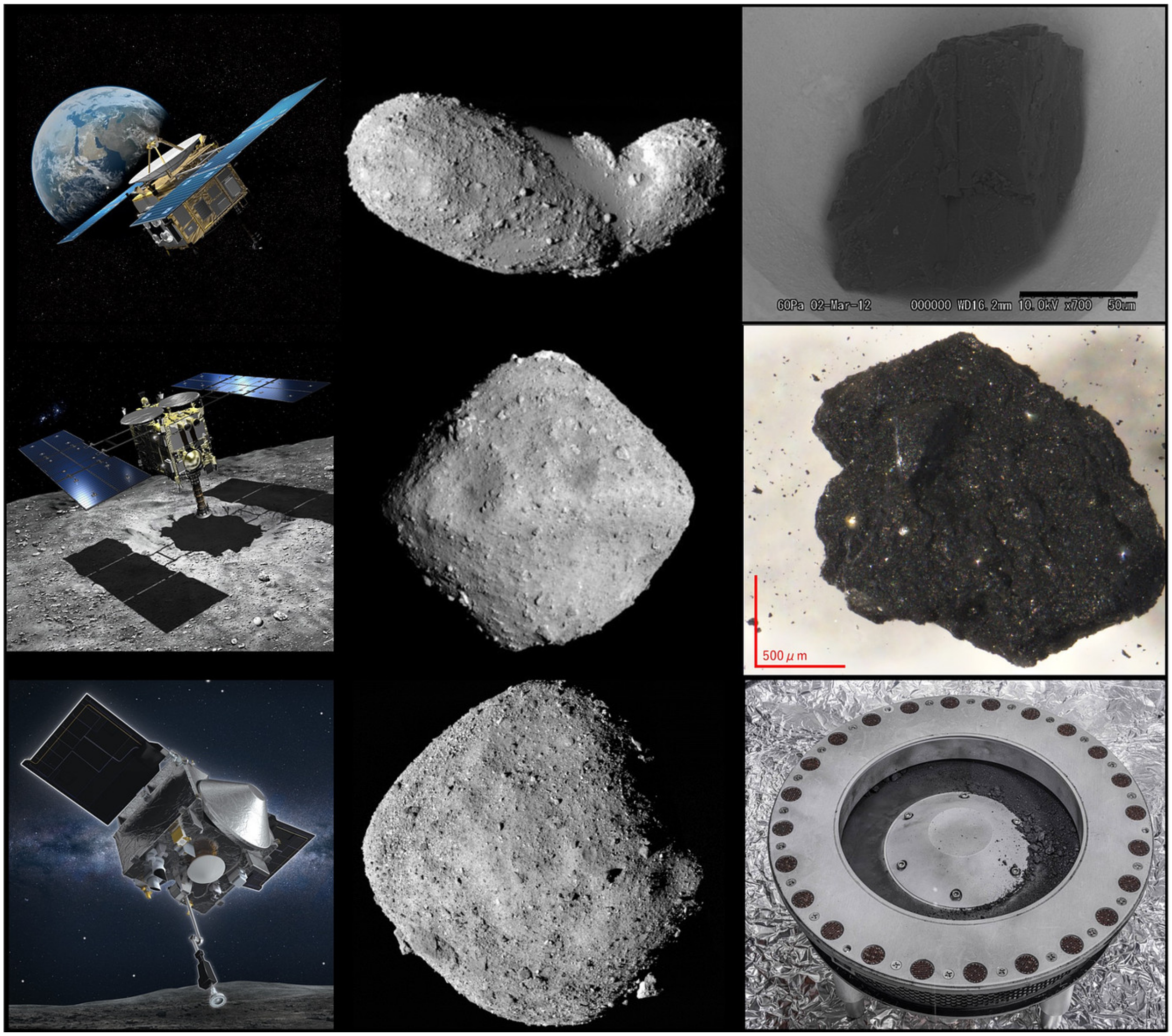


Caption/credit: Since 2021, the Mars 2020 Perseverance rover has been caching samples from Mars’s surface in containers for eventual return to Earth. Credit: NASA/JPL-Caltech/MSSS



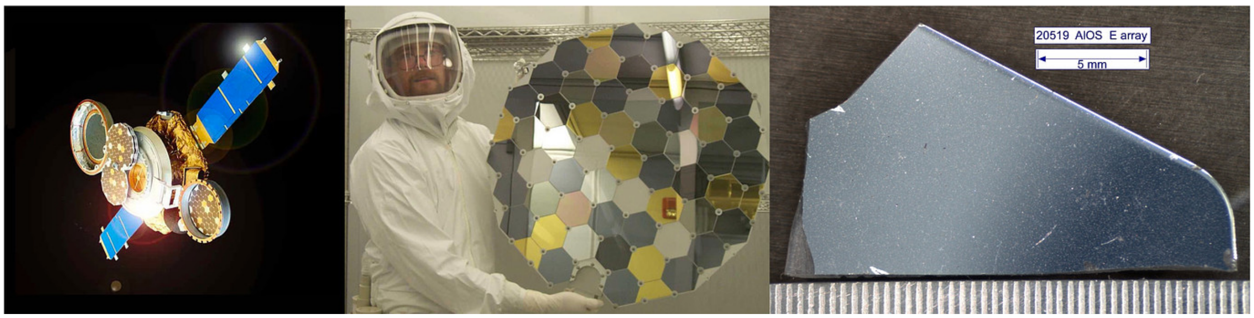
Embed 1 image file name: Figure1 Moon only.jpg

Caption/credit: Scientist-astronaut Harrison Schmitt (left) collects lunar samples with a rake during the Apollo 17 mission's first spacewalk at the Taurus-Littrow landing site in December 1972. Samples gathered during the mission included a lunar troctolites (top center; sample 76535), lunar soil particles (top right; sample 74220), and cores of soil and rock (bottom right; sample 73002). Credit: NASA



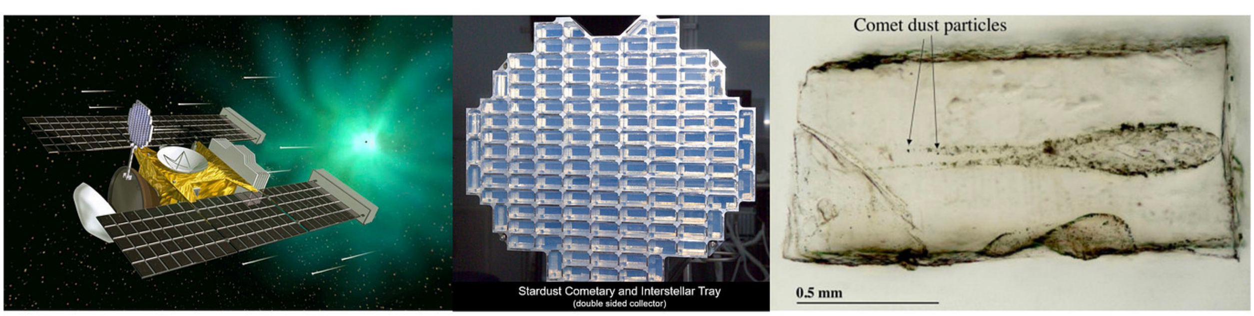
Embed 2 image file name: Figure4 asteroid sample return only.jpg

Caption/credit: Several space missions have returned samples from asteroids. Top: After landing on asteroid Itokawa in 2005, JAXA’s Hayabusa mission returned particles to Earth in 2010. Middle: JAXA’s Hayabusa2 mission arrived at asteroid Ryugu in 2018 and returned samples to Earth in 2021. Bottom: Most recently, NASA’s OSIRIS-REx mission returned samples from asteroid Bennu in 2023 after touching down on the asteroid in 2020. Itokawa, Ryugu, and Bennu are small asteroids—all only a few hundred meters across. All images of spacecraft in this figure are artists' illustrations. Credit: top left, Institute of Space and Astronautical Science/JAXA; top center, JAXA; top right, NASA; middle left, JAXA; middle center, JAXA; middle right, NASA; bottom left, University of Arizona/NASA Goddard Space Flight Center; bottom center, NASA/Goddard/University of Arizona; bottom right, NASA/Goddard/University of Arizona



Embed 3 image file name: Figure2 Genesis only.jpg

Caption/credit: NASA's Genesis mission, seen in an artist's rendering (left), launched in 2001 and returned samples of the solar wind in 2004. Samples were gathered using collection arrays, one of which is displayed (center) by a technician before the mission launched. A fragment of one of the arrays (right) after its return to Earth is also shown. Credit: NASA



Embed 4 image file name: Figure3 stardust only.jpg

Caption/credit: NASA’s Stardust mission, seen in an artist’s rendering (left), launched in 1999 and returned samples from the tail of comet Wild2 in 2006. Samples were gathered using the Stardust cometary and interstellar collector tray (center). In the collector, comet particles were captured in a material called aerogel (right). Credit: NASA