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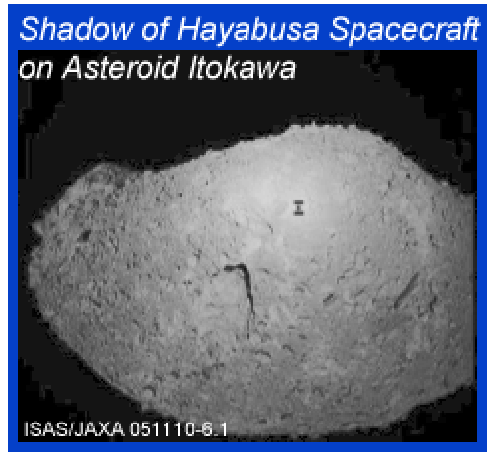

Headline Article
August 31, 2011

Samples from Asteroid Itokawa

--- Samples returned from asteroid Itokawa by the Hayabusa mission provide ground truth for astronomical observations and reveal that the little asteroid is eroding at a rate of tens of centimeters per million years.

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The Hayabusa spacecraft, flown by the Japanese Aerospace Exploration Agency (JAXA), returned samples from **asteroid** 25143 Itokawa on June 13, 2010. Though the sampling device did not operate properly, the mission was able to return a couple thousand particles, from a few- to a few hundred-micrometers across. A battery of laboratory analyses (electron microscopy, elemental analysis, and oxygen isotopic measurements) shows that the particles derive from materials like those in thermally metamorphosed LL group ordinary **chondrites**. Astronomical observations had classified Itokawa as a stony S(IV) type of asteroid.

The nature of S-type asteroids has been debated for decades; some astronomers argued that S-type asteroids are ordinary chondrites while others suggested that they were more likely to be differentiated objects (i.e., melted or partially melted to make igneous rocks). The problem was that we did not know enough about **space weathering** on asteroids to know how the **spectra** of chondritic or differentiated asteroids changed with exposure to micrometeorites and **solar wind**. The examinations of Hayabusa's treasure have settled the argument: S-type asteroid, Itokawa, indeed has an ordinary chondrite composition whose spectrum has been reddened by space weathering. This conclusion is supported by detailed studies of the surfaces of 10 Itokawa particles, half of which have glassy rims (5-50 **nanometers** thick) containing nano-sized particles of iron sulfide and metallic iron, signatures of space weathering.

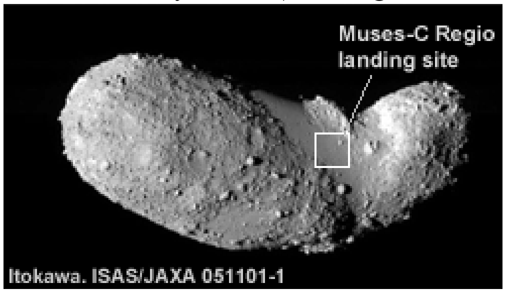
Analysis of noble gases in three particles from the asteroid indicate that they were exposed on the surface of Itokawa for surprisingly short times, less than 8 million years. The Hayabusa science team suggests that the short exposure time indicates loss of particles into space through small impacts at the surprisingly fast rate of tens of centimeters per million years. This might not seem fast, but the asteroid, only 535 x 294 x 209 meters in size, would become just a dusty memory in no more than a cosmically-short billion years.

References:

- See full listing of six references at the end of this article. References from **Science magazine**, 26 August 2011 issue.
- **PSRDpresents:** Samples from Asteroid Itokawa --**Short Slide Summary** (with accompanying notes).

The Hayabusa Mission

Hayabusa blasted off from the Kagoshima Space Center in Japan on May 9, 2003. It used solar-powered ion engines to propel itself to asteroid 25143 Itokawa, arriving at a position only seven kilometers from the asteroid on October 4, 2005. From its perch in space it maneuvered around the object (its gravity field was too small to really orbit it), taking breathtaking images and making spectroscopic observations.



[Left] Itokawa is ~500-kilometers long and covered with boulders, suggesting it is a loosely-bound pile of rubble. Its low density, about half of typical chondritic meteorites, also indicates that much of its volume is empty space, typical of rock piles.

The spectral data were similar to those taken with telescopes on Earth and indicated a composition like that of **LL chondrites**. However, there has been a long-standing debate about the interpretation of spectra of the type displayed by Itokawa. Some planetary astronomers are sure that such spectra, called S-type (silicate or stony), are chondrites, as suggested by the Hayabusa team, but others think that the objects are differentiated–that is, chondritic bodies that have melted. The argument focuses on the role of space weathering caused by micrometeorite and solar wind bombardment in altering the spectral properties of asteroidal surfaces (see **PSRD** article: **Space Weathering Agent: Solar Wind**). Settling this debated required a detailed look at samples, hence the Hayabusa mission.

Once the global survey was completed, it was time to collect the samples. Unfortunately, the sampling device on the spacecraft did not operate as planned. The idea was to slowly approach the little asteroid, at about 10 centimeters per second, and when the tip of the sampling device touched the surface it would fire two 5-gram projectiles at 300 meters per second at the surface. The projectiles would both fracture and kick up surface materials that would be captured by a cone-shaped sample catcher. The projectiles were made of tantalum, a metal not found in abundance in meteorites, so would not contaminate the samples. Unfortunately, the pyrotechnic firing system did not activate, so the tantalum bullets did not smack into the asteroid. Undaunted, the Hayabusa mission team boldly adopted an alternative strategy: They decided to land on the asteroid (twice), expecting that the sample catcher would be able to collect at least some material. They were right!

The sample collection device was transferred to the sample return canister and the spacecraft began its long journey back to Earth. It landed in the Australian outback on June 13, 2010.

Retrieval team with the Hayabusa sample capsule shortly after landing in Australia. Courtesy of JAXA.

The problem with the sample catcher was just one of many serious problems during the Hayabusa mission. To list just a few: While on its way to Itokawa, a strong solar flare fried the solar cells that power the spacecraft's electrical systems, including its ion drive. The resulting lower electrical power slowed down its trip, reducing the time it spent at the asteroid. Two reaction wheels failed near the end of the orbital mapping campaign, a big problem because of the fine maneuvering required near the ~500-meter , irregularly-shaped object. Hayabusa engineers decided that they could use small rocket thrusters to control the spacecraft's orientation during the sample collection phase. On the return, two of the four ion drives stopped working and there were some communication problems. Never giving up, engineers kept making adjustments, demonstrating great skill and cosmic tenacity!

Studying the Asteroid Samples in the Lab

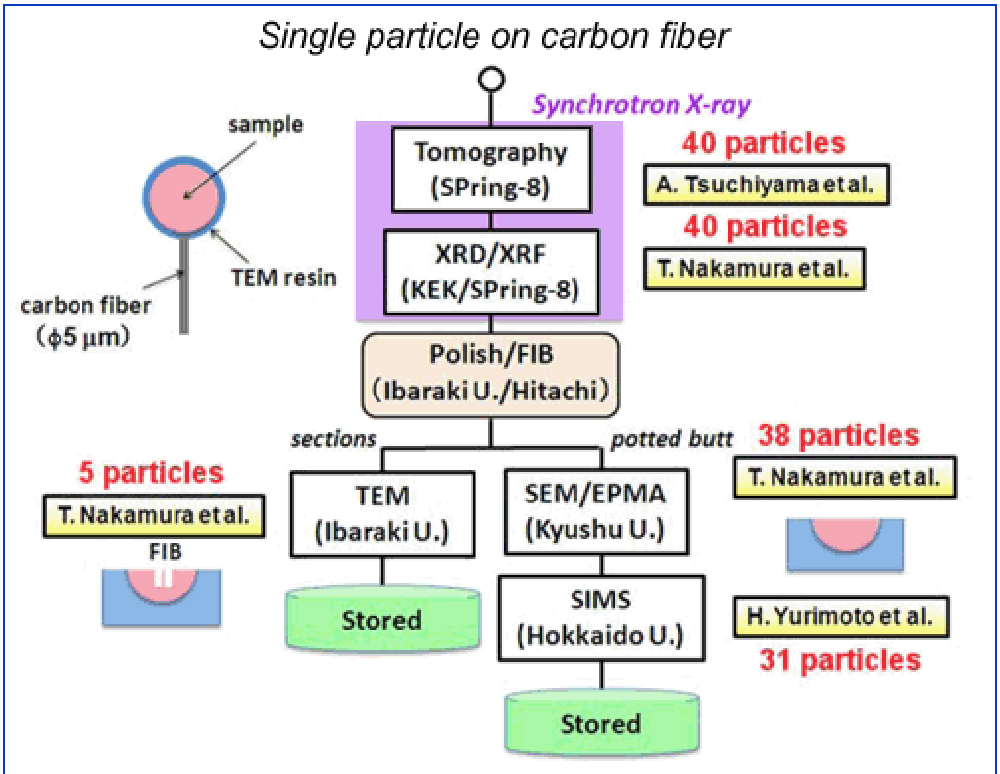
Hayabusa scientists did not expect large fragments of rock to be filling up the sample catchers, so they prepared to collect dust samples. Because the Earth is a dusty place, they had to clean the return canister and its sample collectors in a clean environment. For this, they built an ultraclean chamber equipped with sampling tools. The team collected three types of samples: Individual particles picked out using an electrostatic needle, dust swept up using a Teflon spatula, and dust particles collected on a pure-silica glass surface by thumping the sample catcher; see photos below.

Processing the Asteroid Samples at the Japan Aerospace Exploration Agency

(From Nakamura *et al.*, 2011, *Science*, v. 333(6046), p. 1113-1116, Figs. S3A,B; S4A, doi: 10.1126/science.1207758.)

(A) Electrostatic particle manipulator (arrow) consists of a thin silica fiber with a thinner platinum wire inside it. The silica-platinum line is attached to the end of a stainless steel rod (the arrow actually points to the steel rod). **(B)** The surface of one of the two sample catchers being swept by a Teflon spatula (arrow); 1534 particles collected by this procedure have been studied. **(C)** A pure-silica glass slide (arrow) was screwed into the top of a sample catcher. The catcher was turned upside down and tapped (gently) to loosen particles to allow them to drop onto the clean silica slide. So far, Hayabusa scientists have studied about 40 particles collected by this technique.

Once they collected the samples, scientists had to develop a logical and efficient protocol for studying numerous rocky particles. Fortunately, cosmochemists have experience analyzing tiny grains collected in the stratosphere, returned by the Stardust mission, and removed from carbonaceous chondrites (see **PSRD** article: **Analyzing Next to Nothing**). For the 40 particles separated by whacking the container, the Hayabusa team used the procedures outlined in the chart below, which includes all necessary analyses to characterize the samples and to gain insight into the asteroid's history. For the particles adhering to the Teflon spatula, they were able to transfer the spatula into a scanning electron microscope to examine them and to measure chemical compositions of particles by energy-dispersive X-ray analysis.

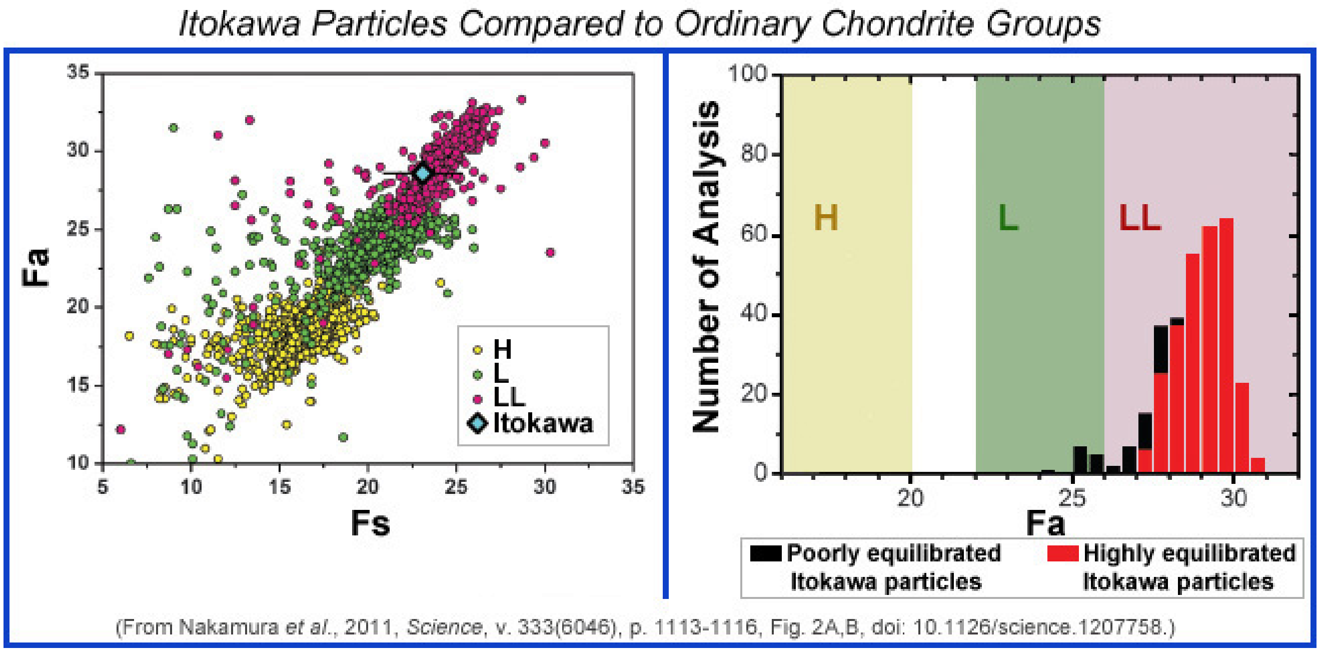


(From Nakamura *et al*., 2011, *Science*, v. 333(6046), p. 1113-1116, Fig. S5, doi: 10.1126/science.1207758.)

Flow chart showing how the 40 particles collected by tapping the sample containers were analyzed by Hayabusa cosmochemists; lead authors of the articles in the August 26, 2011 issue of *Science Magazine* are listed as well. Individual asteroid particles were placed on carbon fibers and studied non-destructively by X-ray tomography (allowing detailed examination of particle shapes), X-ray diffraction (XRD, to allow identification of the minerals present), and X-ray fluorescence (XRF, to enable determination of chemical compositions). These were then polished for analysis by transmission electron microscopy (TEM, for mineralogical studies), more scanning electron microscopy (SEM) and electron microprobe analysis (EMP, for accurate chemical analysis of tiny particles), and secondary ion mass spectrometry (SIMS, for oxygen isotopic analysis). Five particles were also designated to be made into ultra thin slices called FIB sections. Additional particles were separated for destructive analysis such as noble gas analysis (although these were also characterized by scanning electron microscopy before noble gas analysis).

LL Chondrite

Tomoki Nakamura (Tohoku University) and colleagues show that the mean compositions of grains of the iron-magnesium silicate minerals olivine and pyroxene fall squarely in the range of those in LL ordinary chondrite meteorites, as shown in the graphs below. Almost all of the mineral grains are quite uniform in composition, and the entire collection falls almost entirely within the LL compositional field. This indicates that most of the sampled material was thermally metamorphosed, as is the case for most ordinary chondrites. To be heated sufficiently, the samples must have originated inside a much larger asteroid.



[Left] Compositions of low-calcium pyroxene, expressed as the amount of ferrosilite (Fs, $FeSiO_3$) versus the amount of fayalite in olivine (Fa, Fe_2SiO_4). Data from ordinary chondrite meteorites are plotted (H, L, and LL), and the mean value for the Itokawa particles. Itokawa analyses fall within the data points for LL chondrites, showing that it is compositionally similar to that group of chondrites. **[Right]** Histogram of olivine (Fa, Fe_2SiO_4) composition for Itokawa particles, split into those that are uniform in composition (in red) and those that are not as uniform ("poorly equilibrated" in black). The data are in the LL field and dominated by thermally metamorphosed (equilibrated) particles, indicating that Itokawa is a collection of debris from a much larger asteroid that had heated enough to equilibrate the mineral grains.

Other data support the interpretation that Itokawa is similar to LL chondrites. The abundances of oxygen isotopes are useful for distinguishing many types of meteorites and planetary samples from each other. Hisayoshi Yurimoto (Hokkaido University) and colleagues show that Itokawa samples have oxygen isotope compositions in the range of those for L or LL ordinary chondrites. Neutron activation analyses by Mitsuru Ebihara (Tokyo Metropolitan University) and coauthors provide trace element abundances for one tiny particle (it has a mass of only 3 micrograms) that show that its composition is consistent with that of ordinary chondrites. Thus, taken together, it appears that Itokawa has the composition of an ordinary chondrite, most likely an LL chondrite.

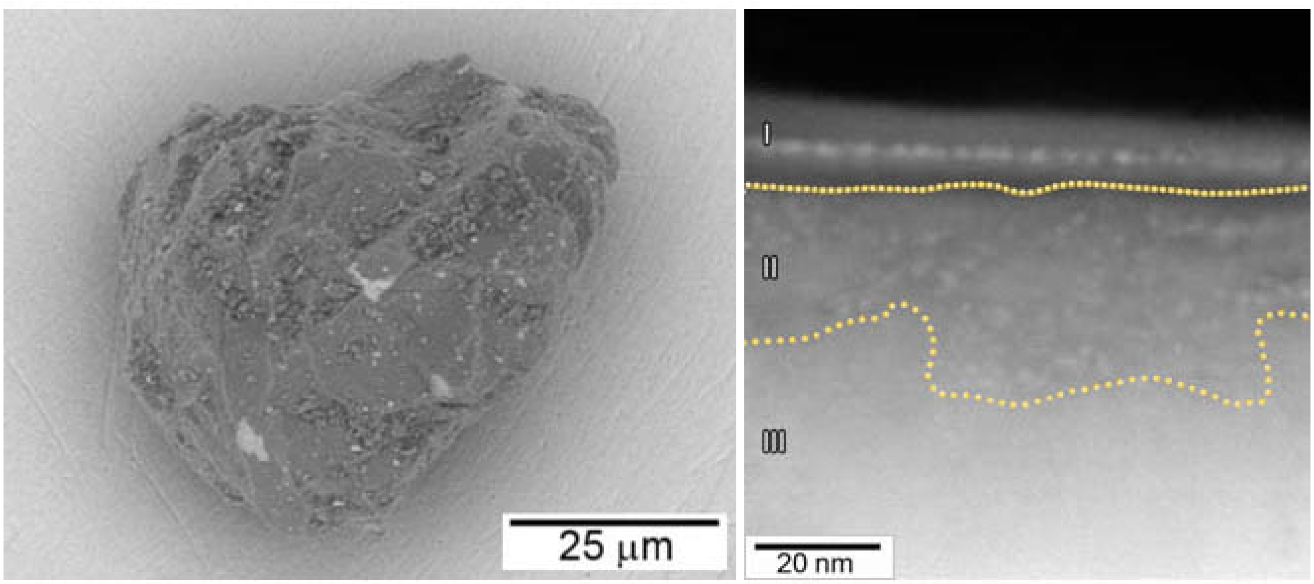
S-Type Asteroids and Space Weathering

Astronomers classify asteroids by the spectrum of the light reflected from them. S-type asteroids were known to be rich in silicates (hence the designation S). They have been the subject of lively debate for over two decades. One school of thought identified them as related to ordinary chondrites, the most common type of meteorite observed to fall on Earth. But the spectra of light reflected from S-type asteroids do not match spectra of chondrites measured in the laboratory. Scientists who advocate that S-type asteroids are chondrites appeal to space weathering. We know from studies of the Moon and lunar meteorites that exposure to solar wind and micrometeorite impacts changes the spectral properties of planetary materials (see **PSRD** article: **New Mineral Proves an Old Idea about Space Weathering**). Before Hayabusa, we did not know the details of space weathering on asteroids. As for the Moon, having samples to study in detail is essential.

The second school of thought interprets S-asteroids as being miniature planets that were chemically processed to varying extents. Some might have melted so much that they formed cores and mantles. Others might have melted partially to form surfaces covered with lava flows. Others might have melted only a tiny amount, causing modest redistribution of rock and metallic iron and iron sulfide. Some S-asteroids have spectra similar to some partially melted meteorite groups, but not all do.

So, before Hayabusa returned its valuable samples, we had a dilemma: Two schools of thought arguing over ambiguous data. Hayabusa solved the problem by showing us that the returned particles are from an asteroid that never melted. At least this one S-type asteroid is a chondritic body. Equally important, the samples give us the opportunity to examine the effects of space weathering on small bodies composed of chondritic rock.

Takaaki Noguchi (Ibaraki University) and colleagues studied the exquisite details of the space-weathered particles from asteroid Itokawa. Their analysis of 10 particles found that half of them have rims in the form of two thin, amorphous (glassy) layers. The surface layer, 5 to 15 nanometers thick, contains sulfur-bearing iron-rich nanoparticles and the underlying layer, 20 to 50 nanometers thick, contains nanophase metallic iron particles. The team attributes the formation of the iron sulfide and metallic iron nanoparticles to space weathering. While multilayered, silica-rich rims containing nanophase iron have been identified previously on mineral grains in lunar regolith, the top layer on these Itokawa particles is something new because of the presence of sulfur in the nanoparticles. The layer, nevertheless, could have been produced by similar space weathering processes known to operate on the lunar surface: Impact vaporization and deposition of nanophase-sized iron. The underlying layer, containing metallic iron nanoparticles, is too deep on these Itokawa samples to be explained by the same process; Noguchi and coauthors suggest that ion implantation from solar wind could have reduced Fe^{2+} to Fe^{0}. They argue that these metallic iron nanoparticles in the space-weathered rims have reddened the spectrum of asteroid Itokawa.



(From Noguchi et al., 2011, Science, v.333(6046), p. 1121-1125, Fig. S1, doi: 10.1126/science.1207794.)

(From Noguchi *et al.*, 2011, *Science*, v.333(6046), p. 1121-1125, Fig. 2, doi: 10.1126/science.1207794.)

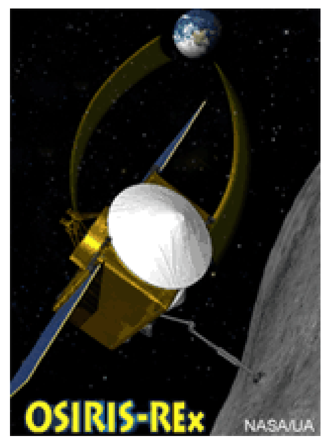
[Left] Backscattered electron (BSE) image of a typical Itokawa particle having a space-weathered rim. **[Right]** High-angle annular dark-field scanning transmission electron microscope image of the layered rim on a low-Ca pyroxene in an Itokawa particle. The yellow-dotted lines indicate boundaries between: (I) outermost layer of amorphous silicate with nanophase iron sulfide grains; see the light-toned spots, (II) partially amorphous layer enriched in (light-toned) nanophase metallic iron grains, (III) unaltered pyroxene.

Eroding Itokawa

Keisuke Nagao (University of Tokyo) and colleagues analyzed the noble gases in Itokawa particles by incrementally heating three small particles (the largest was only 0.2 micrograms) and measuring the amount of gas released with a mass spectrometer. Helium (He), neon (Ne), and argon (Ar) isotopes are informative about the duration of exposure to solar wind and to cosmic rays. (So are isotopes of krypton and xenon, but because of the small size of the particles these gases were not detectable above instrument background.) The measurements detected substantial amounts of He, Ne, and Ar derived from the solar wind, consistent with the particles being exposed on Itokawa's surface. Surprisingly, Nagao and his colleagues found no detectable amount of ^{21}Ne. This isotope of Ne is produced mostly by high-energy cosmic rays, implying short exposure times.

Decades of work by cosmochemists studying the exposure histories of meteorites and interplanetary dust particles have led to well-established rates for the production of ^{21}Ne and other isotopes produced by cosmic ray interaction with space rocks, leading to accurate ways to calculate exposure times. Using data from the largest particle, Nagao and colleagues calculate that the particle was exposed to cosmic rays for less than 3 million years if it was sitting smack on the surface of the asteroid or for less than 8 million years if it was buried about half a meter deep. This is a relatively short time (particles in the lunar regolith have average exposure times of 400 million years), and implies that material must be constantly lost from Itokawa's surface. Nagao and coworkers estimate a total loss rate of tens of centimeters per million years. At that rate, Itokawa will disappear in no more than a billion years.

More Samples to Come



JAXA's Hayabusa mission is one of a series of round-trip sample-return missions being planned by the world's space agencies. We already have had samples of the solar wind returned by the NASA **Genesis mission** and bits of comet Wild 2 returned by the **Stardust mission**. NASA recently selected OSIRIS-REx in its New Frontiers program and JAXA selected Hayabusa-2, both slated to launch within the next five years and return material from asteroids thought to be like carbonaceous chondrites. These samples will be studied by the same laboratory techniques developed over the years by cosmochemists to study meteorites, interplanetary dust particles, and lunar samples. The future samples will allow cosmochemists to make stronger links between asteroids and our incredibly valuable collection of extraterrestrial materials already in hand.

Additional Resources

Links open in a new window.

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