

Chip off the old block: Meteorites are definitively linked to stony asteroids

The parental identification was clinched by analyses of a sample of dust brought from an asteroid to Earth by a Japanese space mission.

The *Hayabusa* spacecraft might well be called the little spacecraft that could. It was launched by the Japan Aerospace Exploration Agency (JAXA) in May 2003 to retrieve a rock sample from the surface of a near-Earth asteroid. That asteroid, shown in figure 1, was provisionally known as 1998 SF36 when first discovered but later named 25143 Itokawa after a Japanese rocket pioneer. In June 2010, despite several mishaps during the mission, the spacecraft managed to deliver back to Earth a capsule containing a wisp of dust (at least 1500 micron-sized particles) from the asteroid's surface. Since then, comments Donald Brownlee of the University of Washington, "analysis teams have done a remarkable job using cutting-edge analytical methods for tiny samples to provide a first-class science return from the mission." The teams reported their findings in six papers in August.¹⁻⁶

One key finding concerns a multi-decade debate about the origin of the meteorites that have pelted Earth's surface since its formation. Most of them are ordinary chondrites—silicate-rich rocks that have not been changed due to melting or differentiation. They are among the oldest rocks in the solar system and hence contain clues about the composition and evolution of Earth and other planets. To put into context the information contained in the meteorites, planetary scientists want to know where the objects came from. The trajectories of a few of them indicate that they came from the main belt of asteroids—also primitive rocky objects—that orbit the Sun in the region between Mars and Jupiter.

The most abundant asteroids in the inner part of the main asteroid belt are the stony, or S (for siliceous), asteroids—a class that includes Itokawa. Their reflectance spectra, as measured by Earth-based telescopes, are close enough to those of meteoritic dust to suggest that the meteorites are made of the same ancient material as the S-class asteroids and hence stem from the same interplanetary region. The meteorites were per-



Figure 1. The asteroid Itokawa photographed from the spacecraft *Hayabusa*. Dust samples were taken from the smooth region near the center known as the MUSES-C Regio. The asteroid, just 535 m long, is sometimes referred to as a "rubble pile" because it was formed by an agglomeration of fragments from a larger parent body that broke up. (Photo courtesy of Japan Aerospace Exploration Agency.)

haps knocked loose from their parent S-class asteroids during collisions.

Alas, the spectra of the two types of objects are just different enough to preclude an unambiguous linkage. In particular, the stony asteroids' spectra display absorption bands that are slightly reduced in intensity and that feature a continuum whose intensity increases as wavelength increases into the near-IR. In a word, the asteroid surfaces appear to be redder than those of the meteorites.

One explanation for the discrepancy is that the asteroid surfaces have been altered by "space weathering," caused by solar wind, cosmic rays, and micro-meteorite bombardment. Such speculation was bolstered 10 years ago when Richard Binzel of MIT and coworkers calculated the impact of surface alteration on the spectrum of an S-class asteroid: They applied a particular model of space weathering to the measured spectrum from Itokawa and found that the resulting curve more closely matched that of meteorite dust.⁷

Analysis of actual grains from Itokawa's surface has now shown that they are indeed made of the same chondritic rock as the meteorites found on

Earth. The measurements also indicate ways in which weathering has changed many of the surface particles. Binzel hails the arrival of the *Hayabusa* sample to finally settle the debate. The sample provides what he calls "ground truth"—a calibration point for their ground-based measurements.

A long wait

Hayabusa made two descents to Itokawa's surface to collect the soil samples. Mission scientists had designed a special sampler that was to fire tiny projectiles at the surface and collect the resulting spray. Because the spacecraft had a harder impact with the surface than designers had intended, the sampler did not fire the projectiles. The experimenters could only hope that some dust had nevertheless made its way into the collection horn.

During the spacecraft's five-year trip back, said Tomoki Nakamura of Tohoku University, he and other mission scientists had no idea whether the collection capsule contained any dust at all. When *Hayabusa* neared Earth in June 2010, it ejected the heat-shielded return capsule, which descended via parachute and landed in the Australian outback.

Six different research groups quickly set to work, bringing to bear a plethora of highly sophisticated measurement techniques to probe different aspects of the dust grains. Several lines of investigation indicate not only that these S-class asteroid particles are chondrites, like meteorites, but that they belong to a particular subgroup known as LL (for very low—or low low—total metallic iron constituents); the two other subgroups of chondrites are H for high total metallic iron and L for low total metallic iron.

One research group explored the composition of Itokawa grains by measuring the ratios of various elemental constituents such as iron or magnesium in the grains.¹ When those ratios are plotted against one another, as in figure 2, rocks in the same chondritic subgroup appear in the same region of the plot; the mean value determined from the Itokawa sample puts it squarely in the region of LL rocks. The same conclusion was reached by another group, which measured the modal abundances of minerals in the sample dust.²

The link between the Itokawa dust and chondritic meteorites was further upheld by a research team that explored such compositions as the nickel-to-cobalt ratio, measured by means of neutron activation analysis,³ and by researchers who determined the oxygen isotope ratios.⁴

To explore the impact of space weathering, one group of experimenters looked at the compositional layering of the asteroid grains.⁵ In half of the samples—ones containing iron-bearing minerals such as olivine—the 5- to 15-nm-deep layer near the surface contained nanometer-sized particles rich in iron, sulfur, and magnesium. The next layer down, ranging from 20 to 50 nm deep, contained abundant metallic iron nanoparticles. The surface coatings of iron and sulfur nanoparticles may have been laid down by vapor deposition following bombardment by micrometeorites, or perhaps they were created by solar wind irradiation and sputter deposition. The presence of metallic iron in the surface layers of these grains may well explain the observed reddening of the asteroid's spectrum. Indeed, nanophase iron caused by space weathering is known to account for the spectral reddening seen on the Moon.

Other findings

Some of the researchers found that most, but not all, of the dust particles had a rather homogeneous distribution of elemental inclusions, indicating that

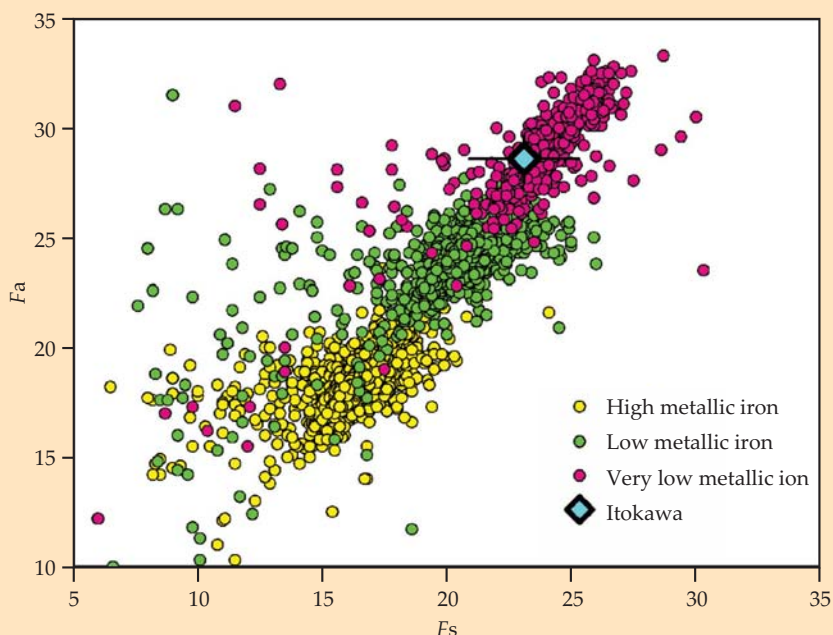


Figure 2. Ratios of metallic content separate chondrites (ancient silicate-rich rocks) into three general subgroups. Subgroup H has high amounts of metallic iron (Fe), L has low metallic iron, and LL has very low metallic iron. The mean values of ratios measured in Itokawa dust particles place the asteroid in the LL subgroup. The y-axis, F_a , is the ratio (in percent) of total mass of iron (Fe plus FeO) to the total mass of iron plus magnesium in olivine crystals. The x-axis, F_s , is the ratio of total iron to the sum of iron, magnesium, and calcium in low-calcium pyroxene. (Adapted from ref. 1.)

those grains had been annealed at temperatures as high as 820 °C, probably in the interior of Itokawa.¹ For the asteroid to have been that hot implies it must have been 20 km in diameter compared with its maximum dimension today of 0.5 km. The explanation, say Nakamura and his colleagues, is that “Itokawa is made of reassembled pieces of the interior portions of a once larger asteroid.”

Itokawa's lifetime is expected to be much shorter than that of the solar system because of the rate at which it is losing mass from its surface: roughly tens of centimeters every million years. Researchers reached that conclusion by measuring the abundance of noble gases implanted by the solar wind.⁶ They then estimated the time it would have taken for a grain to accumulate the observed concentration of a given isotope. In the case of neon-21, the estimated exposure time is at most 8 million years. Any grains older than that appear to have escaped from the asteroid, whose gravitational pull is weak.

The asteroid dust is only the second type of unaltered sample brought to Earth from the surface of an extraterrestrial body, the first being Moon rocks returned by lunar missions. Other missions have sampled the “stardust” from the tail of a comet and particles of the solar wind. The asteroid data already

indicate ways in which the weathering on Itokawa's surface differs from that on the Moon.²

The *Hayabusa* mission has just whetted the appetite for more asteroid samples. Two missions being planned have set their sights on exploring asteroids rich in organic and water-containing minerals. Japan Aerospace Exploration Agency is already working on a follow-up mission, *Hayabusa-2*, and hopes to launch the spacecraft by 2014 to retrieve samples from a C (for carbonaceous)-type asteroid. In the US, NASA is planning the OSIRIS-Rex mission to visit another carbonaceous asteroid by 2016. And the European Space Agency is considering an asteroid-sample return mission called *MarcoPolo-R*. Nakamura for one is certainly hoping for much larger samples the next time around.

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