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PERSPECTIVE

Adventures in Near-Earth Object Exploration

Erik Asphaug

Asteroids, because of the hazard they pose to Earth, are compelling targets for robotic and human space exploration. Yet because of their exotic low-gravity environment, simply landing on an asteroid appears to be much more challenging than we had appreciated 5 or 10 years ago. Thanks to a bold new mission from Japan that has made the first asteroid sample return attempt, this goal is now within our reach.

Calling upon the poetry of Yeats to describe the near-failure of the risky Hayabusa mission at asteroid 25143 Itokawa might seem overly dramatic, but his words seemed all too appropriate late last year: "The falcon cannot hear the falconer; / Things fall apart." Hayabusa (Falcon) had lost communication with Deep Space Control at ISAS, the Institute of Space and Astronautical Sciences of the Japan Aerospace Exploration Agency (JAXA). Its hydrazine had leaked away shortly after the second sample collection attempt. Two of the reaction wheels had failed and the battery was dead. Adding insult to injury, Minerva—intended to be the first asteroid surface robot—had been released during an unexpected maneuver and was lost to space. "The centre cannot hold." Yet despite these heartbreaking setbacks, Hayabusa has been a stunning success both for asteroid science and for deep space concept testing, as reported in an exciting set of mission reports in this issue. These are the rewards of heroic efforts to make things go right in the face of multiple setbacks.

Failures are not uncommon in deep space, and in this case ingenuity and perseverance have paid off in remarkable ways. Hayabusa is the first spacecraft to visit one of the small (diameter ~300 m) asteroids that regularly come whizzing past Earth; it has returned startlingly clear images of Itokawa's rubble surface and made the most important asteroid mass and compositional determinations since NEAR [NASA's Near Earth Asteroid Rendezvous mission (*1*)] mapped the asteroid 433 Eros. The Hayabusa mission has also been a trial by fire of what works and does not work in spacecraft engineering and mission planning. The key instruments that performed well (the imaging camera, laser altimeter, near-infrared spectrometer, and x-ray fluorescence spectrometer) have delivered a treasure trove of knowledge that enhances our understanding of near-Earth objects (NEOs). NEOs are not only important scientifically—our planet formed from them—but have also become political hot potatoes, given the growing pressure to "do something" to mitigate the risks they may pose to Earth.

Asteroid Itokawa is by all accounts as typical as they come—an elongate rocky body a few hundred meters across, spinning a couple of times a day, and belonging to the common S spectroscopic class of rocky asteroids. There are literally thousands of asteroids just like it on Earth-crossing orbits, many of them battered fragments from larger common parent bodies. It is remarkable that it took half a century of spaceflight to achieve reconnaissance with one of them. Itokawa is among the easiest asteroids to visit, requiring low launch velocity. It crosses the orbits of Earth and Mars (Fig. 1) in its 1.5-year orbit around the Sun.

The Hayabusa results indicate that Itokawa is probably a chondritic rubble pile. Chondritic meteorites are the original space rocks that never underwent differentiation into core and mantle. S-type asteroids appear to be composed of the undifferentiated "raw stuff" of planet formation: olivine, pyroxene, metallic iron, plagioclase, and sulfides. The primary source region for S asteroids—along with presumably more primitive carbonaceous C types, metallic M types, igneous V types, and others—is the main belt between Mars and Jupiter. From here, asteroids get scattered by gravitational and thermal forces. The rocks of Itokawa have been battered for millions of years, or billions if you count its existence as part of a larger (but never melted) parent body that dates back to the beginning of solar system time.

After making detailed analyses of Itokawa's incredibly blocky and complex surface, Hayabusa descended for a sample collection campaign described by Yano *et al*. (*2*). Site selection was a major challenge: There was no bedrock per se to sample, and around the largest massifs there were too many spacecraft-sized rocks. Looking for something reasonably flat, the sample return team selected an area equivalent to a gravely beach, the Muses Sea (Fig. 2). It is unknown whether any samples actually made it into the belly of the spacecraft.

This is an exhilarating first taste of surface operations at an asteroid. From the touch-

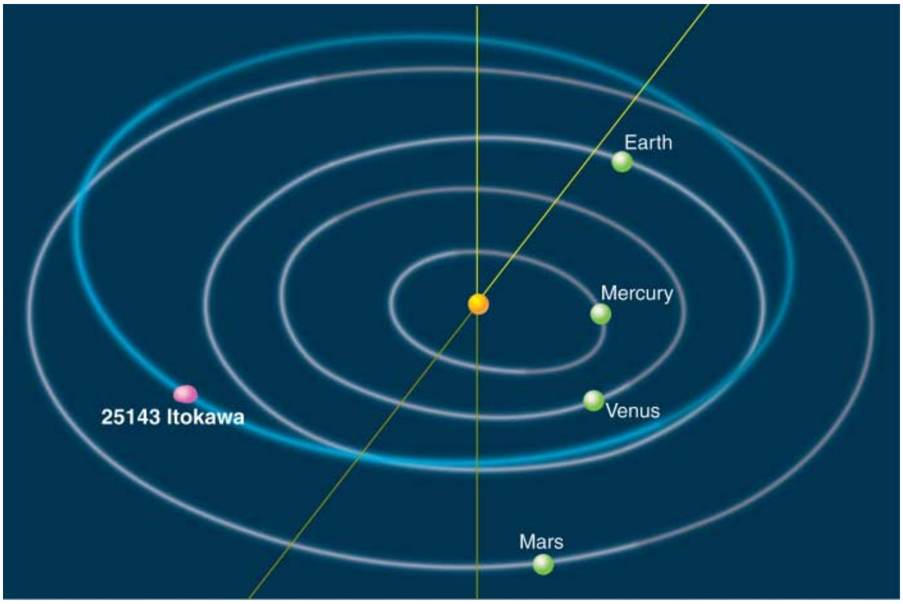

Fig. 1. This orbital diagram, which can be generated at http://neo.jpl.nasa.gov/orbits, shows asteroid Itokawa along with the terrestrial planets. Positions are plotted for 17 September 2008; planets revolve counterclockwise. Itokawa regularly crosses the orbits of Mars and Earth, making its long-term orbital evolution chaotic. Earth-crossing asteroids like Itokawa are potentially hazardous but may also someday serve as ferryboats between the planets.

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down sites we see with high resolution the textures of asteroid surface materials: fine gravels in the very smoothest areas (not the fine powders that were found on Eros) and boulders that are imbricated, possibly a relic of past metamorphic layering. Saito *et al.* (*3*) discuss the plethora of boulders and absence of craters—features that, in combination, suggest that impact reverberations (*4*) might be erasing the craters and sorting out the boulders [e.g., (*5*)].

Most asteroid scientists had not expected to find Itokawa to be a rubble pile; its gravity, smaller than that of Earth by five orders of magnitude, was thought too small to hold it together. It is not even clear why Itokawa is there at all, given that you just have to shake it gently at about 10 cm/s (escape velocity) for it to fly apart. But Itokawa hangs on to its pieces. It seems to be nothing but pieces: a sediment-world governed by ballistic mobilization and pulverization, seismic shaking by impact, vibrational size sorting, low strain rate flow of charged granules, complex gravitational dynamics, dust levitation by photoionization, and solar wind winnowing of lofted dust. Weird stuff. Impact craters are resurfaced as quickly as they form, and smooth deep gravel beds ("seas") are found. One cannot help but wonder how an asteroid will respond to an astronaut's first bootprint. Will it be crunchy? Will she sink? Will clouds of dust rise up?

The infrared (*6*) and x-ray fluorescence (*7*) spectroscopy experiments onboard the orbiting spacecraft have determined that Itokawa is probably chondritic in composition. This is in concordance with the NEAR spectroscopic investigation of Eros (*8*), another S-type asteroid. The density of an ordinary chondrite meteorite is around 3 to 3.5 g/cm^3. Abe *et al.* (*9*) use laser altimetry and spacecraft telemetry to derive the mass of Itokawa (3.5×10^{10} kg), giving a density value (1.9 g/cm^3). If chondritic, it must have a porosity around 40%, which is greater than the porosity of sand and about as loose as you can possibly pack a rock pile. Itokawa would have to be extremely loose rubble all the way down (*10*). This is consistent with spacecraft measurements and what we know of the impact evolution of asteroids, but the true test awaits a mission devoted to interior exploration that may include, for example, penetrating radar, seismological, and cratering experiments.

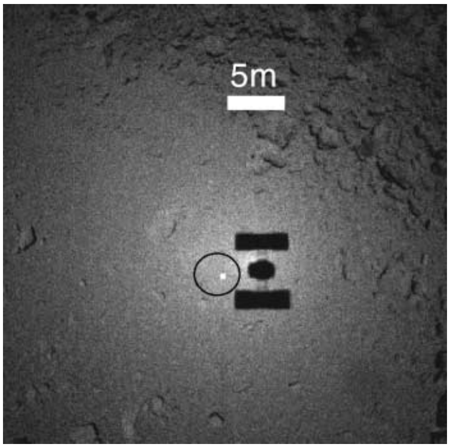

Fig. 2. Pictures from the landing on Itokawa show Hayabusa's shadow on the Muses Sea and the bright target marker dropped onto the surface, into which 880,000 names of supporters from 149 countries are etched. The marker was used for touchdown autonavigation. [Image: ISAS/JAXA]

From afar, Itokawa looks like a potato; close up, it is a crystalline sea otter. The lumpy oblong shape (*11*) is common to small asteroids and may arise from gravitational instabilities where mass is shifted under repeated peppering by meteoroids. Alternatively, asteroids may take on a lumpy shape the way an old bar of soap does, by wearing down unevenly, or they may consist of reaggregated matter from a bigger impact that broke up a much larger parent body, or from a catastrophic tidal passage near Earth. How about the merger of two asteroids from the same family that collided at relatively low velocity? Hypotheses for Itokawa's origin and a careful elucidation of the physics pertaining to these curious whirling mountains are found in Fujiwara *et al.* (*10*).

With no thrusters for fine control, Hayabusa no longer remains under the subtle gravitational influence of Itokawa and instead orbits the Sun. Communication has been reestablished. Late next year, its seemingly tireless solar electric propulsion system will fire up for a long-shot attempt to limp home with a return capsule that may or may not contain some grams of surface material. But engineers must first bake off the leaked hydrazine condensations, lest they torque the spacecraft during cruise. Then the engines, star trackers, and attitude control systems must all check out. And finally, reentry through Earth's atmosphere must succeed in 2010 with no possibility of late-course correction.

If the account of Hayabusa sounds worthy of a novel, the European Space Agency (ESA) has come up with Don Quijote, a dual-spacecraft mission designed to tilt at these windmills of rock and ice. The first of the duo, Sancho, will enter orbit early and place a surface payload, including seismometers, on an asteroid not yet selected. The second spacecraft, Hidalgo, arrives at much higher speed a year later. It will make a big crater in the manner of NASA's Deep Impact mission to comet 9P/Tempel 1 (*12*). This time, though, in situ instruments will characterize the impact, the formation of an almost natural new crater, the aftermath of seismic shaking, landslides, erasure of prior craters, and even satellite formation. You could easily spend US$700 million on Don Quijote; the budget indicated by ESA is substantially less. Perhaps given budgetary realities, NEOs—which belong to everyone—are destined to be probed in partnership. Europe, Japan, the United States, Russia, China, and other nations bring complementary interests, resources, and technologies to the table.

NASA has taken a leadership role in asteroid exploration: NEAR was the first asteroid mission, and Galileo acquired the first spacecraft images of an asteroid. Yet NASA has not committed to a spacecraft exploration strategy for NEOs. Unlike lunar and Mars exploration, which are being pushed from the top, NEO missions are pushed from below, in principal investigator–led competition. No new NASA Discovery missions were selected in the last round, which included a handful of proposals to fly to NEOs. NASA has budgets and timelines for outer solar system exploration, for Mars exploration, and for the Moon; where is the plan and the timeline for these objects that come closest to Earth, that strike Earth, and from which Earth originally coalesced?

If we are seeking a new vision for human exploration in space, it should be emphasized that astronauts could visit a small NEO without developing a lot of new space hardware. Veteran astronaut Jones and his colleagues (*13*) have put forward a mission concept where a modified Soyuz crew vehicle, refueled and docked to the International Space Station (ISS), takes astronauts on a several-month "vacation" to rendezvous with an Earth-approaching asteroid, returning to the ISS for stories of adventure to be told around the galley. Perhaps asteroids are the logical, achievable first focus for human rocketry beyond the Moon; if so, then missions such as Hayabusa are paving the way.

References

1. J. Veverka *et al.*, *Science* **289**, 2088 (2000).
2. H. Yano *et al.*, *Science* **312**, 1350 (2006).
3. J. Saito *et al.*, *Science* **312**, 1341 (2006).
4. J. E. Richardson, H. J. Melosh, R. Greenberg, *Science* **306**, 1526 (2004).
5. E. Asphaug, P. J. King, M. R. Swift, M. R. Merrifield, *Lunar Planet Sci. Conf.* **32**, abstract 1708 (2001).
6. M. Abe *et al.*, *Science* **312**, 1334 (2006).
7. T. Okada *et al.*, *Science* **312**, 1338 (2006).
8. J. I. Trombka *et al.*, *Science* **289**, 2101 (2000).
9. S. Abe *et al.*, *Science* **312**, 1344 (2006).
10. A. Fujiwara *et al.*, *Science* **312**, 1330 (2006).
11. H. Demura *et al.*, *Science* **312**, 1347 (2006).
12. M. F. A'Hearn *et al.*, *Science* **310**, 258 (2005).
13. T. D. Jones *et al.*, in *The Future of Solar System Exploration, 2003–2013*, M. V. Sykes, Ed. (ASP Conference Series, vol. 272) (Astronomical Society of the Pacific, San Francisco, 2002), pp. 141–154.

10.1126/science.1128496