MISSIONS TO ASTEROIDS: JOURNEYING TO THE BEGINNING OF OUR SOLAR SYSTEM

An exciting era of scientific exploration of asteroids is underway. Following on the success of NASA's 2001–2004 Genesis and 1999–2006 Stardust missions, which returned samples of solar wind, cometary, and interstellar dust grains, two international missions boldly set their targets on returning samples of asteroids. These fascinating planetary bodies (many of which have not been altered since their formation 4.5 billion years ago) and the meteorites derived from them are giving us vital insights into the formation of our Solar System and, in particular, the formation of our own planet. The Japan Aerospace Exploration Agency (JAXA)'s Hayabusa mission recently returned materials from asteroid 25143 Itokawa. NASA's Dawn mission currently has a spacecraft orbiting the second most massive asteroid in the Solar System, 4Vesta. In addition, future samples are slated to be returned from carbonaceous chondrite parent bodies by JAXA's Hayabusa-2 mission (proposed launch in 2014) and NASA's OSIRIS-Rex mission (proposed launch in 2016). Here we touch on the highlights of the just-completed Hayabusa mission and present news from the in-flight Dawn mission.

THE HAYABUSA MISSION

The Hayabusa spacecraft, developed by JAXA, returned samples from the surface of asteroid 25143 Itokawa on June 13, 2010 (Fig. 1). It was the world's first asteroid sample-return mission, and it brought back about two thousand particles, many of which are polymineralic, ranging in size from a few to a few hundred microns.

The Hayabusa mission tackled the most basic question, namely, the composition of the asteroid. Previous work using ground-based visible and near-infrared spectroscopic observations showed a red-sloped S-type (silicate-rich) spectrum for Itokawa and a surface composition corresponding to that of ordinary chondrite meteorites reddened by space weathering. In particular, spectral characteristics and modeled olivine/pyroxene contents of the asteroid closely matched those of the LL chondrite group (see, for example, Binzel et al. 2001). But some researchers disagreed with this conclusion. The wide array of chemical analyses conducted on the Itokawa particles yielded results consistent with LL chondrite composition. Nakamura et al. (2011) used electron microprobe analyses to show that the ferrosilite content of the pyroxene grains (Fs_{23}) versus the fayalite content of the olivine grains in these samples (~Fa_{28}) plots in the field of the LL group ordinary chondrites (Fig. 2). In addition, the vast majority of the mineral grains were uniform in composition, indicating that the material had been thermally metamorphosed—most likely inside a much larger asteroid—in order to have obtained the degree of heating necessary to reach equilibration temperatures. Oxygen isotope data (Yurimoto et al. 2011) and neutron activation analyses yielding trace element compositions (Ebihara et al. 2011) also provide evidence that the material returned from Itokawa has the composition of LL chondrite.

While light spectra from S-type asteroids don't exactly match ordinary chondrites, it has long been argued that these asteroids are "space weathered" ordinary chondrites. Space weathering occurs when materials on the surface of a planetary body (lacking an atmosphere) are implanted with nanophase iron by the solar wind or impacted by micrometeorites. These processes alter the spectra of planetary materials. Noguchi et al. (2011) studied materials from Itokawa to determine the extent of space weathering. About half the grains they studied did indeed exhibit an altered rim. They determined that metallic iron nanoparticles within these rims were implanted by space weathering processes and that the nanoparticles altered (reddened) the spectra of 25143 Itokawa.

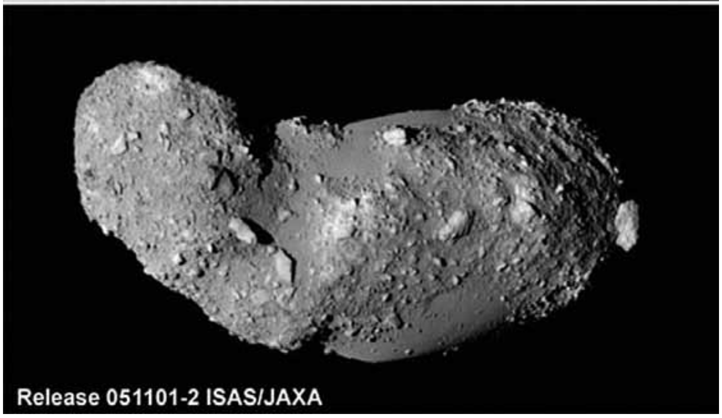

FIGURE 1 The asteroid 25143 Itokawa, measuring 0.6 km in its long dimension. PHOTO CREDIT: ISAS/JAXA 051101-2

One of the most surprising results to come out of research on the Hayabusa samples is that the asteroid is actually shrinking! Nagao et al. (2011) performed noble gas analyses and detected ^{21}Ne, which is produced mostly by exposure to high-energy cosmic rays. They calculated that the samples could not have been on or near the surface for more than 3–8 million years and inferred that the surface of Itokawa must be losing material at a rate of tens of centimeters per million years! For more general information, visit www.jaxa.jp/projects/sat/muses_c/index_e.html or www.psrd.hawaii.edu/Archive/Archive-Asteroids.html.

THE DAWN MISSION

In September 2007, the NASA mission named Dawn (which, in addition to U.S. instruments also carries instruments provided by Italy and Germany) began its eight-year journey to two asteroids, 4Vesta and 1Ceres, located in the main belt between Mars and Jupiter. In July 2011, almost 4 years after the launch, Dawn arrived at its first target, Vesta. With a diameter of 530 km, Vesta is the largest asteroid in the main belt with a basaltic crust and differentiated interior, as indicated by spectroscopic observations and geochemical models (McCord et al. 1970; Righter and Drake 1997; Thomas et al. 1997). It is also the likely

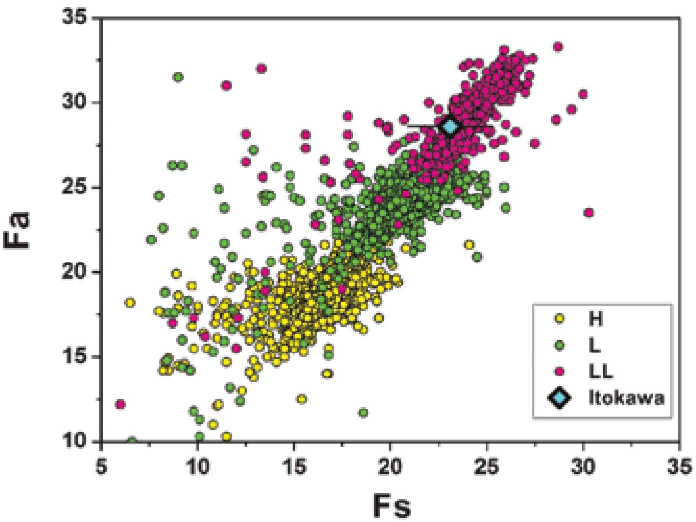

FIGURE 2 Compositions of low-calcium pyroxene expressed as the amount of ferrosilite (Fs, $FeSiO_3$) versus the amount of fayalite in olivine (Fa, Fe_2SiO_4). Ordinary chondrite meteorites are shown as H, L, and LL. The mean value for Itokawa samples (diamond; Fs_{28} and Fa_{23}) plots within the LL chondrite field. IMAGE FROM NAKAMURA ET AL. (2011), REPRINTED WITH PERMISSION FROM AAAS

parent body of the most voluminous group of differentiated meteorites, the HEDs. These meteorites are comprised of crustal basalts (eucrites), plutonic ultramafic rocks (diogenites), and brecciated mixtures of these two components, which likely formed via impact on the surface of Vesta (howardites). Radiometric dating of these samples has constrained Vestan differentiation to a few hundred million years after the first condensates in our Solar System. Petrologic analyses of the HEDs has led to several differentiation models to be proposed for Vesta (McSween et al. 2011), and it is anticipated that these will be tested further with the ongoing observations by Dawn.

Since its arrival in July 2011, Dawn has revealed several interesting structural features on Vesta, which have aided our understanding of protoplanetary formation in the early Solar System. The most noticeable of these features is a large impact basin and central uplift structure at

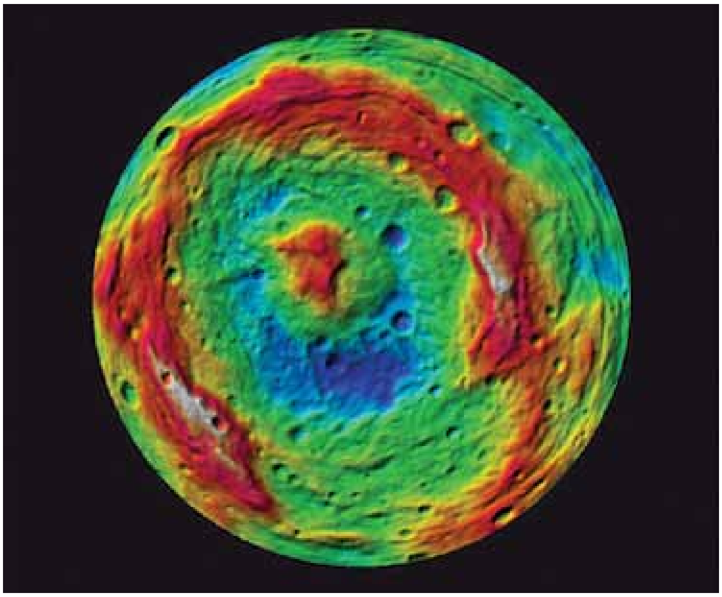

FIGURE 3 False color elevation map of the south pole of Vesta. Scale = –22 km (blue) to +17 km (white) from mean elevation. IMAGE CREDIT: NASA/JPL-CALTECH/UCLA/MPS/DLR/IDA

Vesta's south pole (FIG. 3). This structure has been named Rheasilvia, after a mythical vestal virgin. The basin spans 475 km, or about 80% of the diameter of the asteroid, and the central uplift is ~23 km high, rivaling Olympus Mons (on Mars) in height. Interestingly, impact rebound on a low-gravity body—not convergent tectonics or hot spot volcanism—may have formed the highest mountain in our Solar System. Dawn has also observed interesting structures at the equator and in the northern latitudes. Several sets of coplanar, ~10 km wide trough-and-ridge features circle the equator (FIG. 4) and regions in the northern latitudes. The poles of these coplanar features correspond to the polar regions of Vesta, suggesting that their origin may be linked to the giant impact events that formed the Rheasilvia basin. Along with providing evidence of a dynamic structural history, Dawn has also detected variations in surface composition that have helped test some hypotheses about Vesta's differentiation, predicted by studies of HED meteorites.

The area exposed by Rheasilvia appears to be mostly composed of ultramafic rocks (diogenites), supporting previous conclusions that the diogenite group of meteorites formed as lower-crustal rocks on Vesta. The rest of the surface differs in composition, seeming to be relatively enriched in crustal basalts (eucrite) and brecciated mixtures of basalt and ultramafic rocks (howardite). As Dawn continues to map the surface of Vesta at high spatial resolution, the distribution of these geologic terrains will be constrained, which may provide us with further insight into differentiation on protoplanetary bodies.

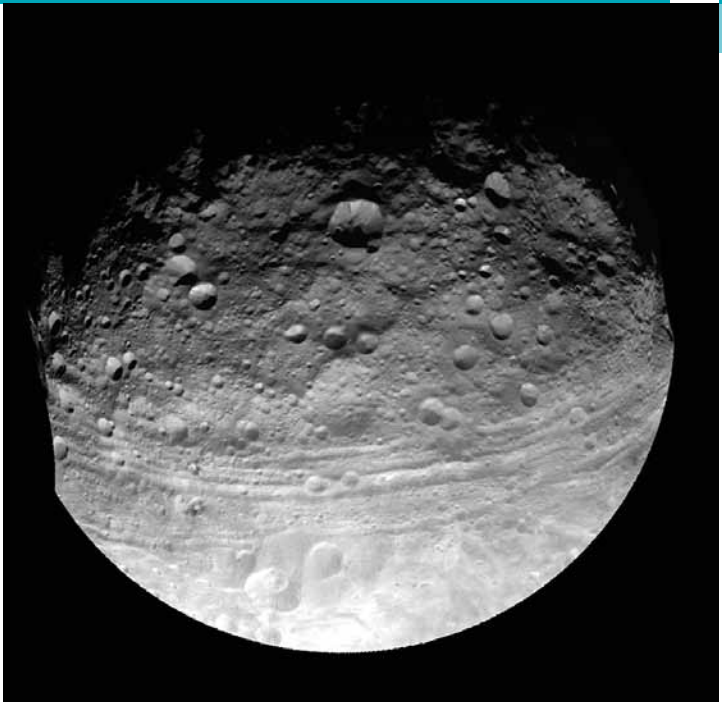

FIGURE 4 Large trough-and-ridge structures seen at Vesta's equator. IMAGE CREDIT: NASA/JPL-CALTECH/UCLA/MPS/DLR/IDA

Dawn recently transitioned into its low-altitude mapping orbit (LAMO), 210 km above Vesta. It will remain in LAMO for 10 weeks, then transition to a higher mapping orbit before departing for its second target, asteroid Ceres, later in 2012. When Dawn reaches Ceres early in 2015, it will become the first spacecraft to orbit two different asteroids and the first spacecraft to visit a dwarf planet. Visit the Dawn homepage at http://dawn.jpl.nasa.gov/ for more information.

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