Dawn Arrives at Ceres

Emily Lakdawalla

NASA's spacecraft enters into orbit around the largest asteroid in the main belt.

It was once called a planet, and then it was demoted. Long passed over for larger solar system targets, this dwarf planet remains mysterious, with an unknown composition and origin. But the mystery won't last long: this year, a long-voyaging spacecraft is finally paying the neglected world a visit.

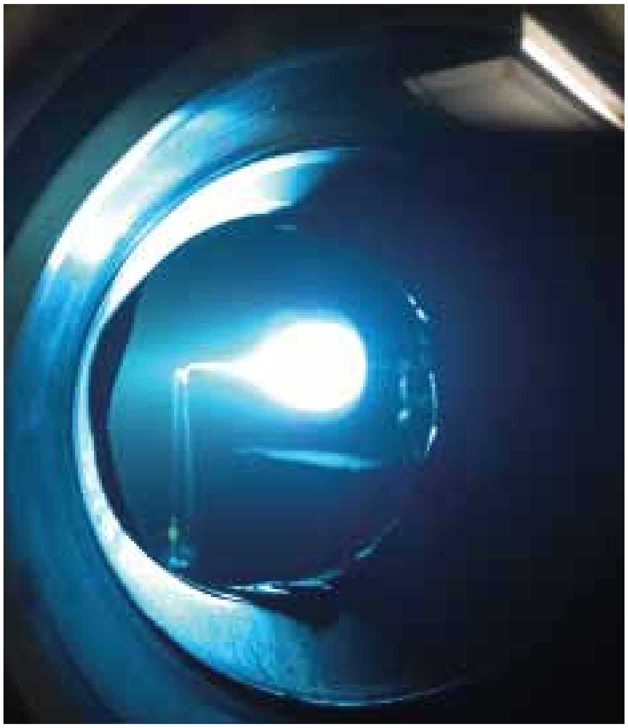
I could be discussing Pluto, but I'm not. Ceres, the first-discovered and largest of the asteroids, is the second target of NASA's Dawn mission. When it arrives at Ceres, Dawn will become the first spacecraft ever to orbit (not just fly by) two worlds beyond Earth.

Dawn is a little spacecraft with a huge wingspan. The spacecraft's small cubical body can mostly hide behind its 1.5-meter (5-foot) dish antenna, but its solar panels stretch nearly 20 meters from wingtip to wingtip. Dawn needs huge solar panels for two reasons. One is distance. Out at Ceres' orbit within the main asteroid belt, the Sun shines only 13% as strongly as it does on Earth. Only two solar-powered missions operate at greater distances from the Sun than Dawn does: the European Space Agency's Rosetta, in orbit around Comet 67P/Churyumov-Gerasimenko, and NASA's Juno, on its way to Jupiter.

The Sun gives Dawn electricity for free, electricity that Dawn can use to accelerate xenon ions to enormous speeds, 7 to 10 times faster than the speed of exhaust from traditional chemical engines. At maximum thrust, each of Dawn's three ion engines expels a miniscule 3.25 milligrams of xenon per second. The resulting thrust

DAWN APPROACHES NASA's Dawn spacecraft bears down on Ceres, the largest main-belt asteroid in the solar system, in this artist's illustration.

ILLUSTRATION BY CASEY REED



NASA / JPL-CALTECH

FULL THROTTLE Although Dawn's xenon ion engine (shown here in the lab) produces a small amount of thrust, that thrust built up over time, eventually propelling the spacecraft to a velocity of about 11 kilometers per second.

is only 91 millinewtons, the same force with which a single sheet of paper weighs on your hand. It's now even less (down to less than 30 millinewtons), for as Dawn's solar separation increases, the solar panels produce less electricity and the engines less thrust. But the patient and near-continuous work of the electrically accelerated ions has propelled Dawn into the record books: it has achieved more change in speed under its own power than any previous spacecraft (10.7 kilometers per second, or 23,900 mph, by the time it gets to Ceres).

It's Dawn's ion propulsion system that makes the mission's two-world navigational feat possible. Having opened our eyes to the marvels of Vesta (*S&T*: Nov. 2011, p. 32), the little spacecraft that could is homing in on a world like none we've seen before. Its size, roundness, and water-rich composition make it seem a kin of Pluto, yet it orbits among the scattered lumpy asteroids. Is it a protoplanet? An escaped Kuiper Belt object? What, if anything, can it tell us about how the solar system formed?

Vesta Success, Flywheel Failure

Dawn launched from Earth in September 2007 and received a boost from a Mars flyby in February 2009. It settled into orbit at Vesta on July 16, 2011, and kept the asteroid company for about a third of its year, until September 5, 2012. Then, Dawn departed Vesta — a rare feat. Only one other mission that has ventured beyond the Moon has ever departed from its deep-space orbital destination: the first Hayabusa mission (also ion-powered), which rendezvoused with Itokawa in September 2005 and departed that December to return to Earth.

Dawn transformed Vesta from a smudge of light into a world with complex geology. Its measurements confirmed that the asteroid has separated into a denser, perhaps metal-rich core and a less-dense rocky mantle and crust. This differentiation is a major driver of internal geology, and planets and moons that are differentiated are also usually round and would therefore be classified as dwarf planets. But after it differentiated, Vesta suffered not just one but two enormous impacts, both near the south pole, which left huge scars on Vesta's three-dimensional shape. An enormous mountain sticks out of its south pole, and its equator is girdled with rhythmic troughs, fossil waves from an impact that nearly blew Vesta apart.

One of the most intriguing features Dawn saw at Vesta was so-called "dark material" in splotches and sprays found across much of its surface (but not inside the largest south polar impact basin, Rheasilvia). That dark material contains hydrated minerals and might be carbon-rich. Neither of those types of compounds would have formed where Vesta now orbits, so the dark material probably represents stuff that originally formed much farther away, perhaps beyond Neptune. Any such material that hit Vesta should also have struck Ceres and all the other asteroids.

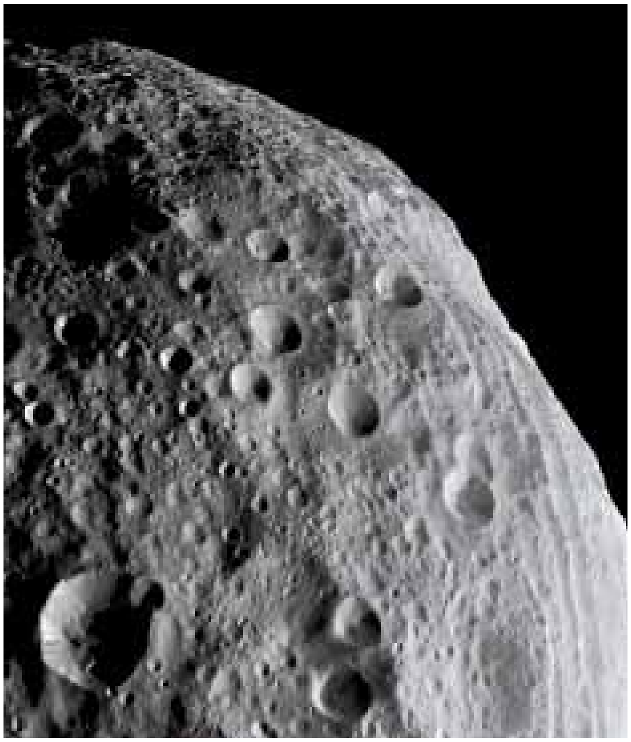
Given Dawn's advanced propulsion system, it's ironic that the Ceres mission was jeopardized by one of humanity's oldest technologies: the wheel. In June 2010, on

HUBBLE VS. DAWN Even Hubble can only resolve fuzzy images of Ceres and Vesta. Shown from left to right are Vesta as seen by Hubble in 2010, a mosaic of Vesta as seen by Dawn, and Ceres in a visible-UV composite from Hubble's view in 2003 and 2004.

approach to Vesta, Dawn lost one of its four reaction wheels. These devices permit the spacecraft to maintain its orientation in space, to keep its solar panels facing the Sun, its dish antenna pointed at Earth, and its instruments aimed at science targets. Because reaction wheels are spun using electricity generated by the solar panels, pointing with reaction wheels is essentially without cost to the mission — unlike the spacecraft's rockets, which have a limited supply of hydrazine to power them.

After the loss of the first reaction wheel, the mission scrambled to conserve hydrazine and preserve the three remaining reaction wheels by using them sparingly. They completed the Vesta mission with three wheels, but a second one ground to a halt as they prepared to depart Vesta in August 2012. Dawn could travel to Ceres without reaction wheels, but it would be impossible to complete the Ceres mission as planned without them: there was simply not enough hydrazine to accomplish all of the required turns.

After herculean effort, the mission's earthly planners succeeded in finding a way for Dawn to complete its Ceres to-do list with no reaction wheels at all. They had to make some compromises: Dawn will not turn to talk to Earth as frequently as it did at Vesta, and will image Ceres only 9 times as it approaches, compared to the 23 imaging sessions it performed on approach to Vesta. But the spacecraft will actually gather more science data at Ceres than in the original plan. Simply by being more patient and waiting a little longer to gather observations, mission planners will be able to acquire everything they promised to at Ceres, including full-color global maps and detailed gravity data.



NASA / JPL-CALTECH / UCLA / MPS / DLR / IDA

VESTA'S BELT Deep grooves wrap around the asteroid Vesta's circumference, likely created by the reverberation from the impact that excavated the Rheasilvia basin at the south pole.

Ceres and Vesta Fast Facts

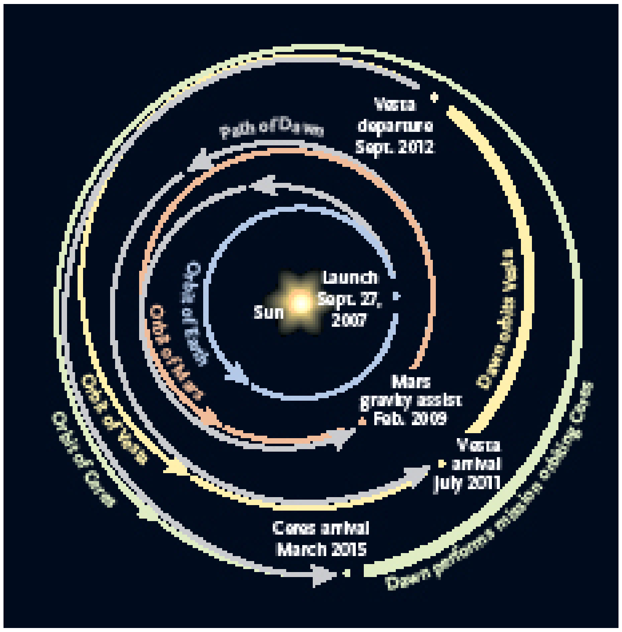
Parameter	Ceres	Vesta
Mean Radius (km)	476	263
Mass (kg)	9.39×10^{20}	2.59×10^{20}
Density (kg/m^3)	2,075	3,455
Rotation Period (Earth hours)	9.075	5.342
Semimajor Axis (a.u.)	2.76	2.362
Eccentricity	0.079	0.0895
Inclination (degrees)	10.6	7.14
Mean Albedo	0.10	0.40

Another Kind of Water World

Ceres is a very different object from Vesta; we know that already, even without visiting it. A key insight into Ceres is its density. Vesta has a bulk density nearly identical to that of silicate rock. Ceres is 80% larger but only two-thirds as dense as Vesta. Yet Ceres is too large for it to have much porosity (unlike smaller asteroids, which can have lots of void space, resulting in low density). There is only one plausible explanation: Ceres contains a substantial amount of water ice.

Given the mass and dimensions of Ceres, and assuming initial proportions of elements like those found in meteorites, geophysicists Tom McCord (now at Bear Fight Institute) and Christophe Sotin (University of Nantes, France) simulated how Ceres would have evolved over time, from a newly condensed mixture of materials to the modern day, 4.6 billion years later. They found that Ceres almost certainly differentiated, its materials separating into a rocky core and watery mantle. Depending on how much of its water is incorporated into the crystal structures of its rocky minerals, its water could compose anywhere from 17 to 27% of its mass. The upper few kilometers of Ceres might always have been too cold for differentiation and so would have remained a mixture of ice and rock. But it's likely that there was a liquid internal ocean for some part of its history, and it's possible that such a liquid layer persists today.

But if this story were true, would there be evidence of it on the surface? Ceres' surface would always have been frozen solid, but as the body's primordial heat escaped, the dwarf planet would have cooled, its ocean slowly freezing solid from the top down. A primitive exterior could hide an evolved interior. On the other hand, any amount



S&T: GREGG DINDERMAN

DAWN'S INTERPLANETARY VOYAGE Using ion-propulsion thrusters and a gravity assist from Mars, Dawn traveled nearly four years to reach Vesta. It's cruised another 2½ years to reach Ceres.

of rock in Ceres' crust would make it significantly denser than an icy mantle below it, which would be an unstable arrangement. Most likely, a primitive crust would founder and sink into the mantle, generating a fresh new surface on the asteroid.

An internal ocean could also drive very active surface geology. Ice is less dense than water, so as Ceres cooled and its subsurface ocean froze, the internal pressure would multiply as this material swelled and tried to take up more space. That internal pressure would have to be relieved somehow. The crust could have cracked in order to allow the mantle to expand, forming planetary stretch marks as a series of parallel fractures, like those we see today on Saturn's moon Dione. If such fractures propagated deep enough to open a conduit to the surface for the pressurized ocean, we could see frozen flows of cryovolcanic material, made of the mineral-rich stuff that once circulated deep within the body. In fact, with its icy composition and differentiated interior, Ceres will likely look much more like the moons of Jupiter or Saturn than it will look like Vesta.

Today, Ceres' surface is too hot for ice to be stable anywhere except, possibly, at the poles. If there ever was ice exposed at the surface, it has sublimed away. Any dust or rocky material that was once buried in the ice would remain on the surface, coating it in a darker, gunky lag deposit made of rocky silicates and organic material. But ice could be very close to the surface. Before it ran out of cryogen in 2013, the European Space Agency's infrared space telescope Herschel made the surprising discovery of water vapor in the space around Ceres — but only at some longitudes, and not at every point in Ceres' orbit. How ice seems to make a patchy, transient water-vapor atmosphere is a new mystery for Dawn to try to solve.

And there's spectroscopic evidence for water's action on Ceres' surface rocks, in the form of minerals never seen on other asteroids: potentially brucite or another hydroxide, and carbonates. The only other places in the solar system where we have observed carbonates are Mars and Earth.

A Pioneer Expedition

Most of the questions driving Dawn's investigation of Ceres are pretty basic, befitting the first reconnaissance of a new world. What covers its surface? How is its interior layered? What is its geologic story? Where and how did it form? Could there ever have been life there?

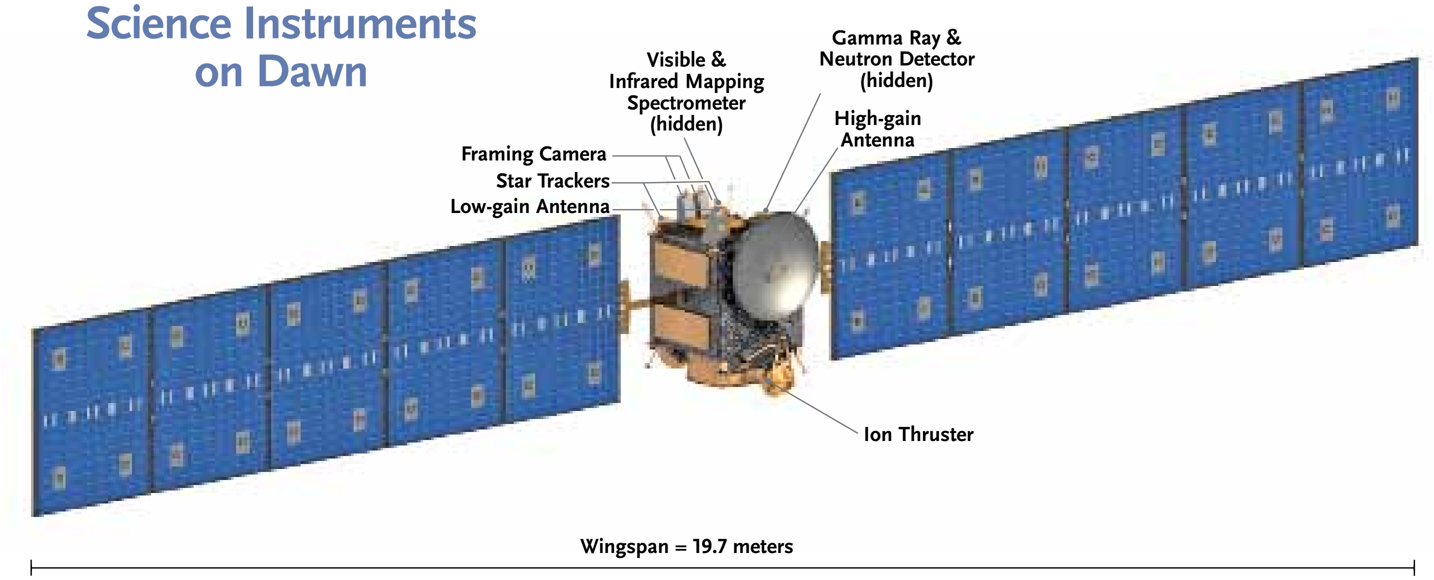
To answer these questions, Dawn will perform a survey of Ceres almost identical to the one it did at Vesta. With its Framing Camera, it will map all of Ceres in full color at medium resolution, and all of it in monochrome at higher resolution. It will gather the data to create a global infrared map with its Visible and Infrared Mapping Spectrometer at low resolution, and some locations at higher resolution. It will also photograph the limb of Ceres against the sky to develop detailed shape models. In a three-month low orbit, Dawn will use its Gamma Ray and Neutron Detector (GRAND) spectrometer to map the distribution of different elements, and radio tracking to measure the gravity field.

Dawn's observations of the shape and gravity of Ceres will significantly narrow the range of possible structures for Ceres' interior, which will, in turn, tell us which of the possible stories for Ceres' geologic history are more probable than others.

One of the most intriguing questions that Dawn could answer is: where did Ceres form? Until recently, scientists assumed that most of the objects in the solar system, particularly the large ones, have been where they are now since their formation. But we now know that giant planets can migrate, and their migrations wreak havoc with the motions of the solar system's smaller denizens.

Ceres has lots of water, so it can't have formed too close to the Sun. Could it have formed farther away than it is now? Its density overlaps with those of trans-Neptunian objects; researcher Bill McKinnon (Washington University in St. Louis) has gone so far as to suggest that Ceres formed in the Kuiper Belt and was transported to the inner solar system by the same dynamical process that populated the Trojan points of the giant planets' orbits with icy bodies. Olivier Mousis (now at University of Franche-Comté, France) and Yann Alibert (University of Bern, Switzerland) proposed an intermediate history: perhaps Ceres' rocky center formed in the asteroid belt, but it accreted an icy envelope later as it caught up smaller Kuiper Belt bodies that drifted into its path. The ques-

Science Instruments on Dawn



TRAVELING LIGHT Dawn has a comparatively small, but successful, payload. Its monochrome Framing Camera has seven color filters and one panchromatic filter to extract as much detail as possible when mapping asteroid surfaces. The Visible and Infrared Mapping Spectrometer detects wavelengths from 250 to 5000 nanometers, covering a wide range of signatures, and its Gamma Ray and Neutron Detector maps elements' distributions across the asteroids' surfaces. CASEY REED, SOURCE: NASA / JPL-CALTECH / UCLA / MCREL

tion of where Ceres formed could be settled with help from GRAND measurements of the ratio of radioactive potassium to thorium. Potassium is more easily evaporated away than thorium, so the ratio between these two elements can change depending on the temperatures an object has experienced in the past — and, therefore, where an object hails from.

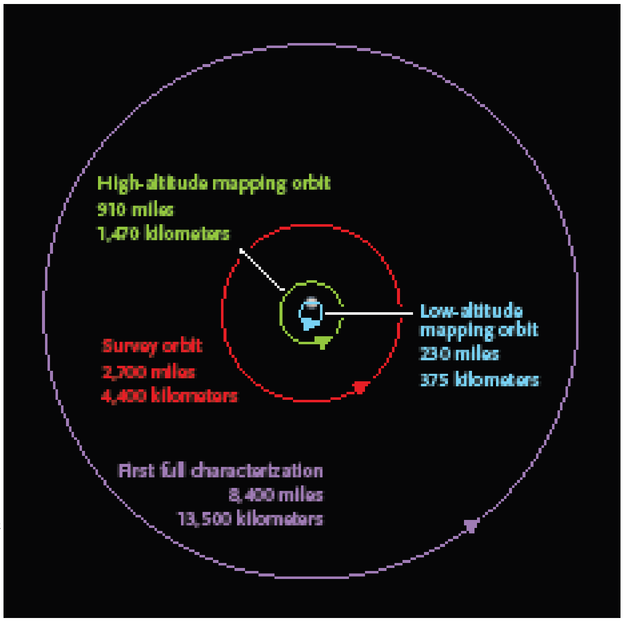
Each of these potential histories could leave its signature in the composition of Ceres' surface and the patterns of its geologic features. For instance, several of the possible stories for Ceres suggest times in its history when it would have needed to change in size. Ice expands as it freezes, and minerals in silicate rocks exposed to liquid water change to other minerals with lower densities than the original ones. If Ceres expanded, we should see *extensional tectonic features* on its surface such as fissures and fractures, possibly even signs of volcanism.

Even if Dawn does not reveal extensional tectonic features, we should be able to detect subsurface ice through the shapes of craters: ice flows over geologic time even if it remains solid, so craters on an ice-rich body should have a relaxed appearance like those on Saturn's moons Tethys or Rhea. If Ceres has features like this, it will be the only place we've ever seen them where the geology wasn't driven by the tidal forces exerted by a neighboring planetary body. Even Pluto and Charon — to be visited by New Horizons in July this year — will have tectonics that are dominated by the forces that the members of that binary world system exert on each other.

But there's also the possibility that Ceres will keep its secrets hidden. Maybe these changes happened so long ago that they've been obscured by dust and space weathering. Some of the features that Dawn spotted on Vesta that were originally thought to be volcanic — including the splotches and wisps of dark material on the asteroid's surface — are now thought to be organic-rich material brought in later by impacts, completely unrelated to Vesta's internal geology. Whatever exogenic processes we see on Vesta, we should also see on Ceres.

CERES LOOKALIKE? Suspected to have a water-ice mantle that influences surface features, Ceres might look more like Saturn's moon Rhea than it does Vesta.

NASA / JPL-CALTECH / SPACE SCIENCE INSTITUTE



SOURCE: NASA / JPL-CALTECH, S&T: GREGG DINDERMAN

SCIENCE ORBITS Dawn will conduct four different orbits around Ceres, spiraling down from the outermost to the innermost over a few months.

What we do know about Ceres is that it is large, it is unmistakably round, and it is brighter in some places than in others. Those three facts make it very likely that Ceres has an exciting story to tell.

Looping an Asteroid

Dawn's science plans for Ceres are very similar to the survey it performed at Vesta, with a few tweaks. Dawn began its approach observations of Ceres in January 2015. The very first images Dawn acquires during approach will be similar in quality to Hubble's of this little world, and they will only get better from there.

As Dawn approaches, it will take nine sets of photos of Ceres while also searching nearby space for possible moons. These will include perform two "rotation characterizations," where it will watch Ceres through one complete 9-hour day, imaging the entire globe with both camera and spectrometer in visible and infrared bands.

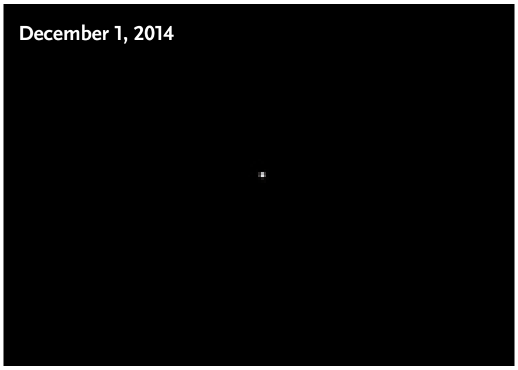
Dawn will arrive in its first science orbit in late April, a polar one at an altitude of 13,500 kilometers (8,400 miles), with a leisurely orbital period of 15 days. That's far enough away for Ceres to still fit comfortably within the Framing Camera's field of view, around 700 pixels across. Dawn will watch Ceres rotate through three complete Cerean days, thoroughly characterizing its three-dimensional shape. Once its orbit takes it to Ceres' nightside, it will repeat the observation, capturing what will be an exciting set of images of Ceres in a crescent phase.

It will take a month for the gentle pressure of Dawn's ion engines to shift it down to its survey orbit altitude of 4,400 km, where the spacecraft will spend three weeks acquiring global maps with camera and spectrometer. Another six weeks of orbit adjustment will take it to its high-altitude mapping orbit, circling Ceres once every 19 hours at an altitude of 1,470 km. A 12-orbit cycle will carry Dawn over every inch of Ceres' surface. From this high-altitude orbit, Dawn will cover Ceres six times — once looking straight down, and the rest at a variety of angles in order to measure what may be subtle topographic rises and falls.

Finally, Dawn will perform its last orbital shift, descending to a low-altitude mapping orbit only 375 kilometers above the surface, about the same as the International Space Station's orbit above Earth. Here, its GRAND spectrometer will be able to most strongly sense the sparse neutrons emanating from Ceres' surface; over time, their energies and locations will tell the Dawn team about the distribution of chemical elements.

While GRAND is mapping the surface, Dawn will also stay in nearly continuous contact with NASA's Deep Space Network. From tiny shifts in Dawn's orbital speed as it circles Ceres, the mission team will be able to map Ceres' gravity field, looking for clues to its internal structure. Dawn will also acquire image data — the highest resolution of the mission — during the lowest orbit, but the focus of this phase is composition and gravity mapping.

In low-altitude mapping orbit, Dawn will prolong its hydrazine supply by switching to a "hybrid mode" of pointing, where it will use its two remaining functional



DECEMBER: NASA / JPL-CALTECH / UCLA / MPS / DLR / IDA; JANUARY: NASA / JPL-CALTECH / UCLA / MPS / DLR / IDA / PSI

LAND HO! Ceres was a dot to Dawn's Framing Camera at a distance of three Earth-Moon separations (*far left*). When the distance closed to match the Moon-Earth system, Dawn saw mottling and a bright spot.

NASA / JPL-CALTECH

ONLY SO SERIOUS Dawn chief engineer and mission director Marc Rayman (JPL) smiles at the camera on the mission's launch day in 2007.

reaction wheels in combination with hydrazine thrusters to point itself. Hybrid mode will also extend Dawn's life as long as possible. But if, at any point, one of its remaining two reaction wheels fails, it will complete its mapping mission on hydrazine thrusters only.

Regardless of whether the reaction wheels survive until mission's end, Dawn should be left with just a few kilograms of hydrazine propellant when its work in the low-altitude mapping orbit is complete. The orbit is a stable one and the spacecraft will never crash into Ceres. It is possible that NASA will extend Dawn's mission: more time for GRAND in low-altitude orbit will improve its maps, and will fill in gaps in high-resolution imaging.

Had the reaction wheels not failed, Dawn could have finished the Ceres mission with sufficient xenon to depart and travel to a third asteroid destination (although who knows whether it would have). Sadly, that is now out of the question. But there should be no regret. Dawn will remain the first spacecraft ever to rendezvous with, orbit, and completely map two alien worlds. And if all goes according to plan, its results will surely be spectacular. ✦

Keep up to speed on the mission with mission director Marc Rayman's Dawn Journal: http://dawnblog.jpl.nasa.gov.

S&T *Contributing Editor* ***Emily Lakdawalla*** *is senior editor and planetary evangelist for The Planetary Society. She writes about space science and exploration at* **www.planetary.org**.
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