Astrophotography: SHOOTING AN ECLIPSE ANALEMMA p. 66

Test Report: 3 MINI MEADE SCOPES p. 58

Lunar Mystery: THE BESSEL RAY p. 52

THE ESSENTIAL GUIDE TO ASTRONOMY

SKY & TELESCOPE

Triangulum Galaxy in Depth p. 54

Observing: 12 Steps to Infinity p. 24

DECEMBER 2016

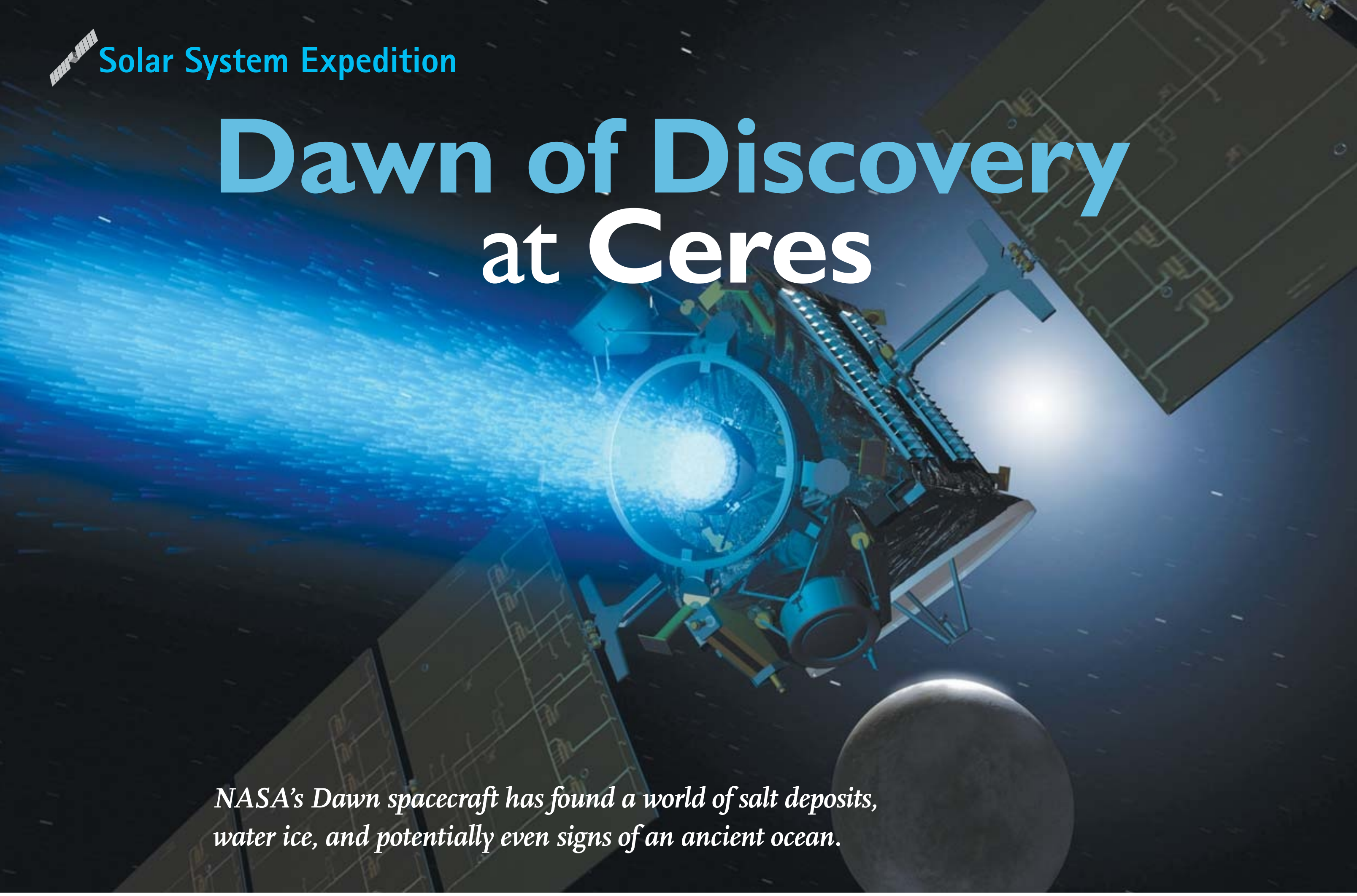
Revealing Pluto's Moons p. 36

The Comets of Edgar Allan Poe p. 30

Dawn's Discoveries at Ceres p. 16

Solar System Expedition

Dawn of Discovery at Ceres



NASA's Dawn spacecraft has found a world of salt deposits, water ice, and potentially even signs of an ancient ocean.

NASA / JPL-CALTECH

Marc D. Rayman

FOR MOST ASTRONOMERS, the arrival of dawn means the end of observing. Intriguing sights become more and more difficult to see, eventually disappearing entirely. Not so with dwarf planet Ceres. The arrival of NASA's Dawn spacecraft in 2015 meant the beginning of more than a year of extraordinary discoveries.

The spaceship left Earth in 2007 on an ambitious journey to explore two giants of the main asteroid belt, Vesta and Ceres. Propelled by its ion engines on a mission to boldly go where — well, you know the rest — Dawn orbited Vesta in 2011–12, revealing a complex body more closely related to Earth and the other terrestrial planets than to asteroids (*S&T:* Sept. 2012, p. 32). It then left to continue its mission to Ceres.

Dawn began approach photography on January 13, 2015, two months before it entered orbit. It was as far from the dwarf planet as the Moon is from Earth. Dawn was designed to conduct a reconnaissance of unexplored worlds from orbit, and it is not equipped with a powerful telescope. From a distance of 383,000 kilometers (238,000 miles), Ceres was only about 27 pixels in diameter. With a resolution of 36 km per pixel, these initial images were not taken to learn about Ceres itself but rather to locate it against the background of stars.

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Navigators needed the images in order to help pin down the position of Dawn's destination accurately so that they could pilot the spacecraft into orbit.

But those very first pictures showed what has become the most famous and mysterious feature: a bright spot. A decade earlier, the Hubble Space Telescope, with resolution of about 30 km per pixel, had detected the spot as well. By the time of Dawn's next pictures, on January 25, 2015, the resolution was one-third better than Hubble's, and the bright spot only grew more salient with those and subsequent pictures. The spot seemed to glow, casting its mesmerizing light out like a cosmic beacon, guiding the way for our interplanetary ship as it sailed the solar system's seas.

Dawn continued to photograph Ceres occasionally prior to its graceful entry into orbit on March 6, 2015, using the gentle thrust of an ion engine. And it has achieved better and better resolution since then, operating in a series of four circular, polar mapping orbits. This has allowed us to progress from an overview of the entire world to an intimate portrait. The best pictures now, taken from an altitude of only 385 km, are one thousand times sharper than the first. Dawn orbits closer to Ceres than the International Space Station does to Earth. From this distance, Ceres appears as large as a soccer ball would when seen from a mere 9 cm (3.5 inches).

As the resolution improved, what initially had appeared as one bright spot became two and soon a multitude clustered together. Scientists and the public alike were captivated by them. NASA's Jet Propulsion Laboratory polled the public for their votes on what the spot was, and more than 190,000 responded. One question I often received was whether it could be the illumination from an alien city. I find such questions disappointing, and I despair of critical thinking. After all, given how little we knew about Ceres, how could we possibly know whether Cereans even live in cities? Perhaps they only live in rural areas, or only in large states. Maybe they only live underground.

Seriously, without taking advantage of the power of the scientific method and thorough consideration of all available data, it is all too easy to reach mistaken conclusions. If understanding an exotic world required only stunning pictures, the work at Ceres would be complete. To unravel Ceres' secrets, scientists integrate results from all of Dawn's measurements and combine them with three more ingredients: comparisons with other solar system bodies, comparisons with laboratory measurements of candidate minerals, and the results of extensive mathematical modeling of the physics, geology, and chemistry. It will take years to put the pieces together to understand the big picture. For now, however, we have only begun to digest the extraordinary bounty from Dawn.

A Salty Spotlight

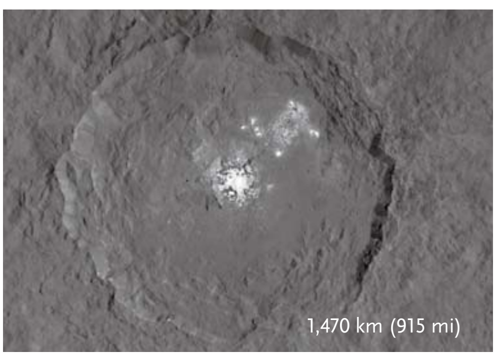
Before Dawn brought Ceres into focus, one popular idea was that the spots could be exposed ice. This idea's appeal might have been due to a report in 2014 that the Herschel Space Observatory had detected the faint but unmistakable signal of water vapor around Ceres. From its orbit around the Sun near the second Lagrangian point, about 1.5 million km from Earth, Herschel was much too far from Ceres to see any detail. But scientists estimated that the amount of water vapor could be explained by only about 150 acres, or 0.6 square km, of ice on the surface. As ice sublimated in the cold vacuum, transforming directly from a solid to a gas, it could produce the extremely tenuous veil of water vapor Herschel detected.

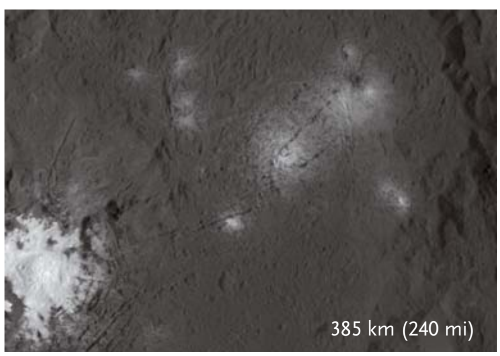
But the bright spots Dawn saw covered too much area to be the source. Even just the central bright region is 500 times larger than the area of ice scientists calculated would yield the detected water vapor. Exposed ice was not a good explanation for the spots.

With similar reasoning, the bright region couldn't have been a cryovolcano or geyser, however exciting that might be. For such a phenomenon to be bright enough for Dawn to detect even with the early, low-resolution pictures, it would have been enormous. Once again, it would not have been consistent with Herschel's findings.

As the "spots" became better resolved, they no longer resembled discrete points but rather a complex distribution of reflective material inside a 92-km-wide crater now named Occator.

Based on all the data acquired so far, scientists consider the most likely explanation for the highly reflective ground cover in Occator to be some kind of salt. It may be that the heating from the impact that created the





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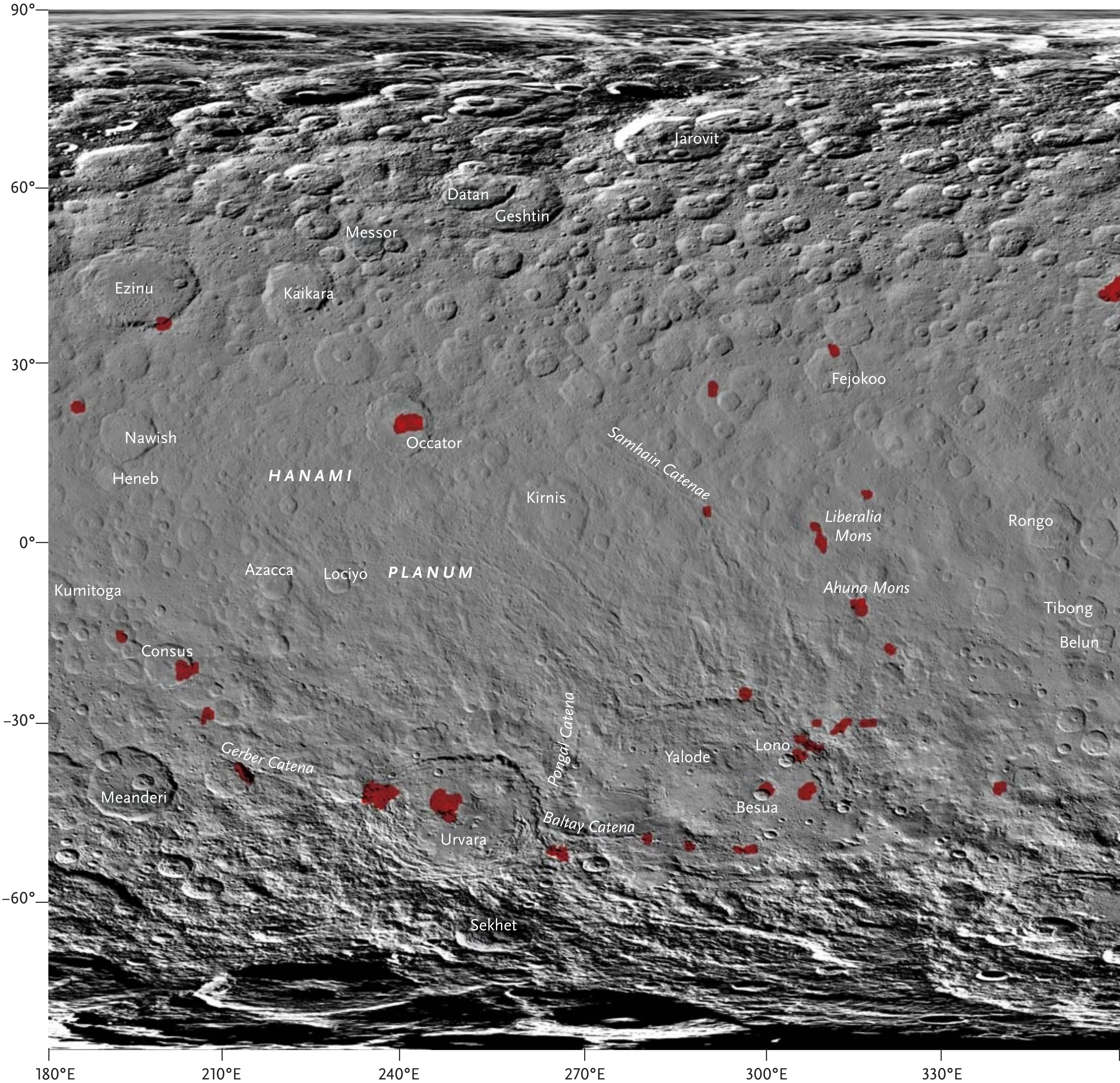
MYSTERIOUS SPOT **Ceres' bright beacon looks like a smudge in Dawn's first approach image *(far left)*. But as the spacecraft neared, the feature revealed itself to be a complex of reflective patches in the crater Occator. Although Occator's "spot" is the brightest, it is only one of more than 130 of these features revealed by Dawn on the dwarf planet.**



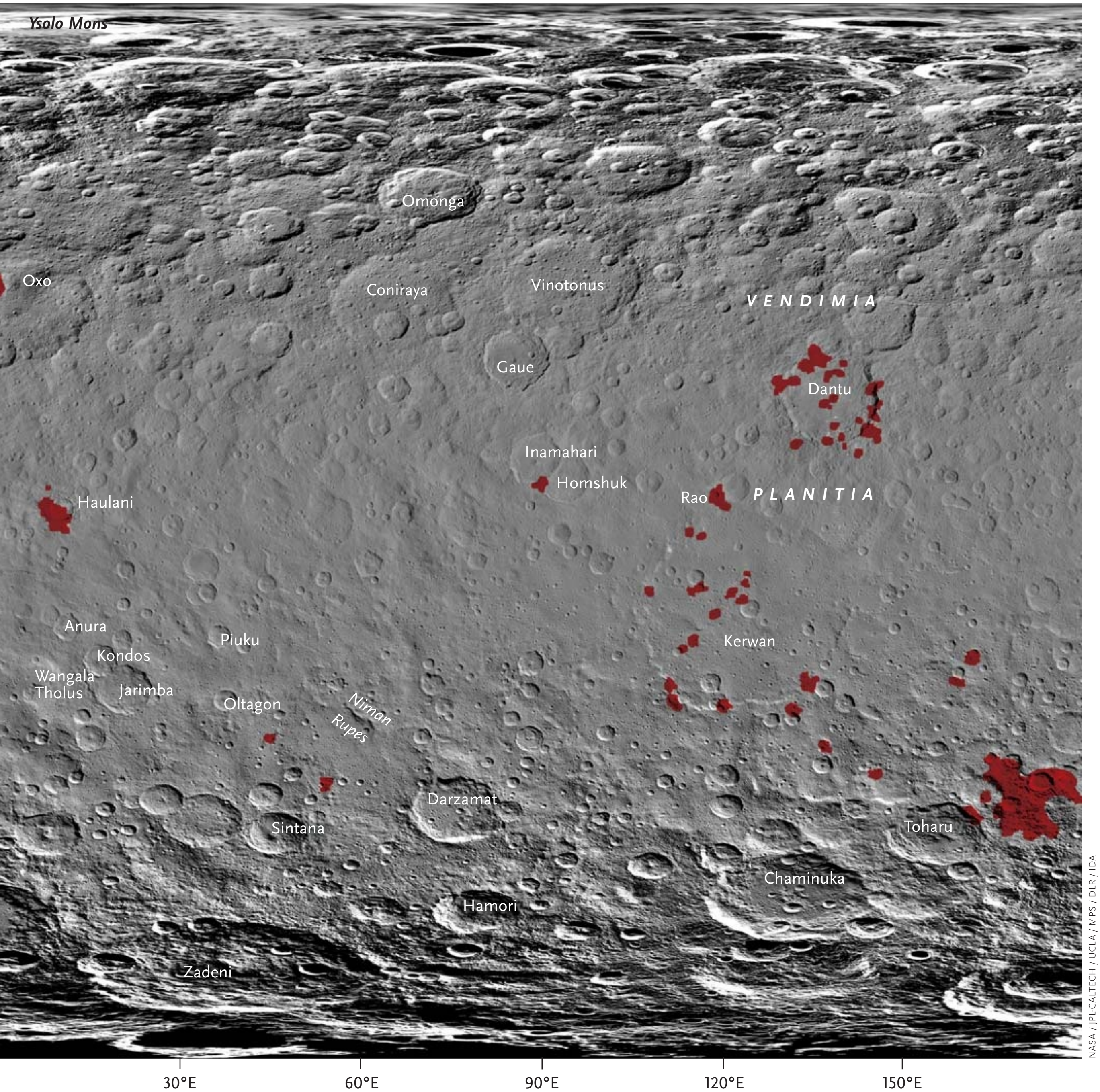
CERES' SURFACE AREA

Ceres spans 2.8 million km² (1.1 million mi²). That's about the area of Argentina, or 35% of the area of the contiguous United States.

crater 80 million years ago caused underground briny water to flow upward to the surface, perhaps through the many cracks visible to Dawn's camera. Once on the cold surface, the brine would freeze. And exposed to the vacuum of space, solid ice would sublimate, the water molecules escaping into space or settling elsewhere on Ceres. When they departed, they would have left behind the dissolved salts.

We base Occator's (tentative) age on the number and size of smaller, more recent craters both within it and on the blanket of ejected material surrounding the crater. That makes Occator young in geologic terms, given that Ceres itself is more than 4.5 billion years old.

Further evidence for the crater's youthfulness comes from it being slightly bluer than most of Ceres. Material tends to redden gradually with exposure to the

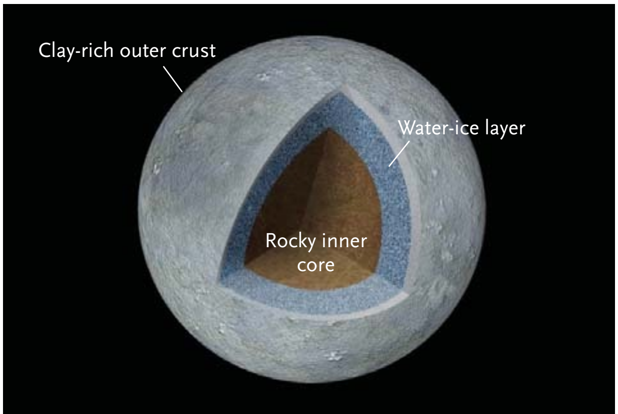


BRIGHT SPOTS GALORE Occator's spots are the most famous, but there are more than 130 other locations on Ceres that are comparatively reflective. Shown here in red are the bright spots' approximate locations, along with a selection of feature names. (For the full list, see the International Astronomical Union's Gazetteer of Planetary Nomenclature: http://planetarynames.wr.usgs.gov.)

space environment for several reasons, two of which are radiation-spurred changes in molecular structure and the breakup of microscopic grains by micrometeoroid impacts. Nevertheless, color is not a definitive indicator of age. For reasons not yet established, the central feature of Occator, the most reflective area anywhere on Ceres, is touched with red, in contrast to the rest of the crater. Occator contains the largest area of highly reflec-

Names on Ceres

The Dawn project and the International Astronomical Union have worked together to name features on Ceres. Giuseppe Piazzi named his 1801 discovery of the largest body between Mars and Jupiter for the Roman goddess of agriculture. All craters are named for deities of agriculture and vegetation from mythology around the world, and other features are named for agricultural festivals.



NASA / JPL-CALTECH

WATER WORLD? Planetary scientists think that Ceres has a large reservoir of water ice beneath its crust.

How Dawn Measures Ceres

Dawn's camera is equipped with eight filters mounted in a wheel in front of its CCD. One admits light across the visible and near-infrared spectrum, from 450 to 920 nanometers. Each of the other seven allows a narrow range of wavelengths from deep blue at 430 nm to near-infrared at 980 nm.

To reveal Ceres' topography, Dawn mapped the dwarf planet from six angles during its third mapping orbit. One map was made by looking straight down at the scenery beneath it. Each of the other five maps was developed by holding the camera fixed at a different angle, looking ahead or behind and to the right or left. Taken together, these create stereo views, making the landscape pop into 3D.

Dawn has four spectrometers packaged in two instruments. Dawn's visible spectrometer, operating from 0.4 to 1 micron (in the near-infrared) would have a view very much like the rainbow created by a prism. The infrared spectrometer works from 1 to 5 microns. A spectrometer does more than simply disperse the light into its components, however. It measures the intensity of that light at the different wavelengths. The materials on the surface leave their signature in the sunlight they reflect, making some wavelengths relatively brighter and some dimmer. This characteristic pattern is called a spectrum. By comparing these spectra with spectra measured in laboratories, scientists can infer the nature of the minerals on the ground. The infrared measurements also yield the surface temperature.

Dawn's Gamma Ray and Neutron Detector (GRAND) consists of two spectrometers that work on the same principle, except with gamma rays and neutrons kicked up from Ceres by cosmic rays. But because the glow of Ceres' nuclear radiation is so faint, GRAND needs to collect data for a very long time, in the same way that photographing a dim object requires a long exposure.

tive material on Ceres, making it the brightest and most conspicuous place on the dwarf planet, but scientists have catalogued more than 130 other locations that also are very reflective. Nearly all of them are bluish.

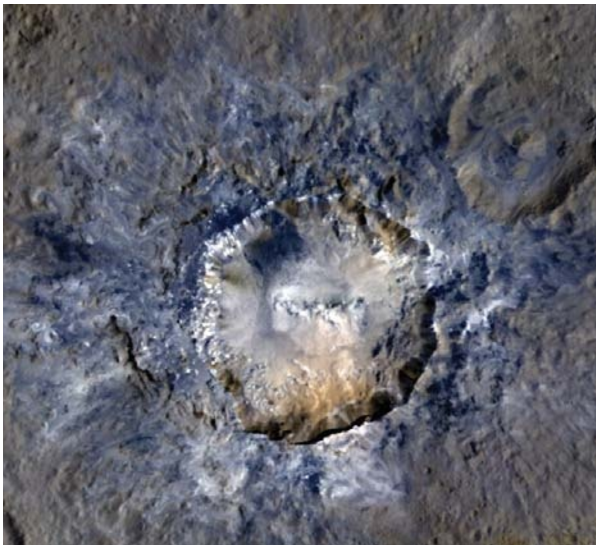
Although 80 million years is geologically brief, it seems much too long for the material in Occator to remain so reflective. Scientists expect that the constant bombardment of small interplanetary debris and cosmic radiation would darken it relatively quickly, so persistent brightness is very difficult to explain. This suggests the intriguing possibility that some geologic process replenished it not long ago. It could be that current or recent activity causes more of that underground salt water to reach the surface and then vaporize, providing fresh salt deposits. This and other explanations are being investigated now.

Water World

The inference of water, most likely frozen, beneath the surface is based on more than the bright areas in Occator. The overall density of Ceres is 2.2 grams per cubic centimeter (g/cm^3). This is surprisingly low, well less than half Earth's density, strongly suggesting that water is a major constituent. (The average dry rock density is 3.4 g/cm^3.) Water may account for about a quarter of the dwarf planet's mass. Ceres then would be the first rocky body with such a large inventory of water orbited by spacecraft, providing opportunities to learn about how such a world works. Other large water-rich places, including Europa and Titan, have not been studied at the level of detail Dawn has achieved from its orbital vantage point.

Dawn also has found signs of water thanks to the compound's interaction with cosmic rays, energetic particles raining down from space. Cosmic rays impinge on Ceres, slam into atomic nuclei in the crust, and produce gamma rays or neutrons that escape back into space. The spacecraft's Gamma Ray and Neutron Detector (GRAND) consists of two spectrometers that record the number and energy of these photons and particles. Measuring them tells us which atoms the cosmic rays hit, down to a depth of about a meter.

While still preliminary, the measurements of neutrons emanating from Ceres indicate that it is rich in hydrogen. The same measurements at Vesta found much less of that element. Hydrogen is a good indicator of the presence of water, which comprises two hydrogen atoms bound to one oxygen atom and is the most common hydrogen-bearing molecule that occurs on solid surfaces. Although the evidence suggests hydrogen is everywhere on Ceres, it is even more plentiful near the poles than near the equator. Researchers are investigating reasons the neutron count might vary with latitude. Their analysis of these complex data may allow them to test the hypothesis that GRAND is sensing ice extremely close to the surface. At higher latitudes, where the



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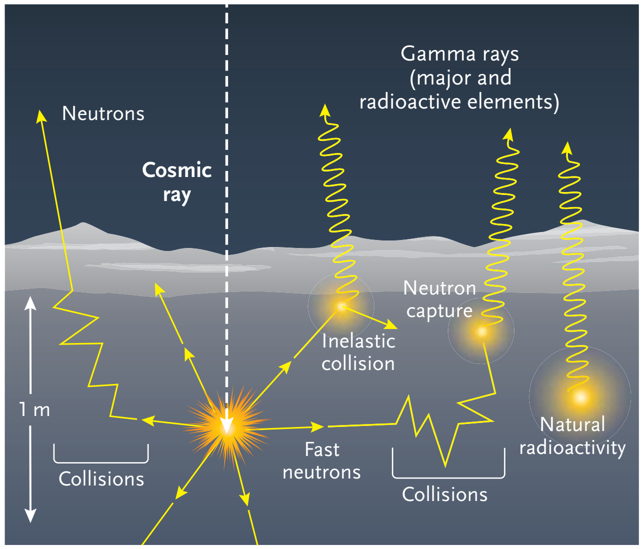

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BLUISH CRATER ***Left:*** **Shown here in enhanced color, the crater Haulani has landslides along its rim, as well as a central ridge. Scientist think the bluish material here (in outlying ejecta) and elsewhere on Ceres is younger than its surroundings.** ***Right:*** **When a high-energy cosmic ray slams into a nucleus in Ceres' surface, the target nucleus "explodes," producing a spray of secondary particles, including neutrons. These particles can collide with other atoms in the regolith, creating gamma rays that escape with other neutrons from the dwarf planet and reach Dawn in orbit.**

distant Sun provides less heat, ice could have persisted throughout Ceres' lifetime, whereas at the warmer low latitudes, it would have retreated to greater depths.

In one location, however, Dawn has already directly detected water. The infrared mapping spectrometer picked up its clear signature in a crater named Oxo, 42° north of the equator. Oxo is relatively small, only 10 km in diameter, but it's the second brightest region on Ceres. (Only Occator is brighter.) We don't yet know whether the water Dawn found there is ice or is bound up in hydrated minerals. However, because exposed ice, if that's what it is, would be ephemeral, it must have arrived on the surface recently. Scientists are still scouring Dawn's infrared spectra for signs of water elsewhere.

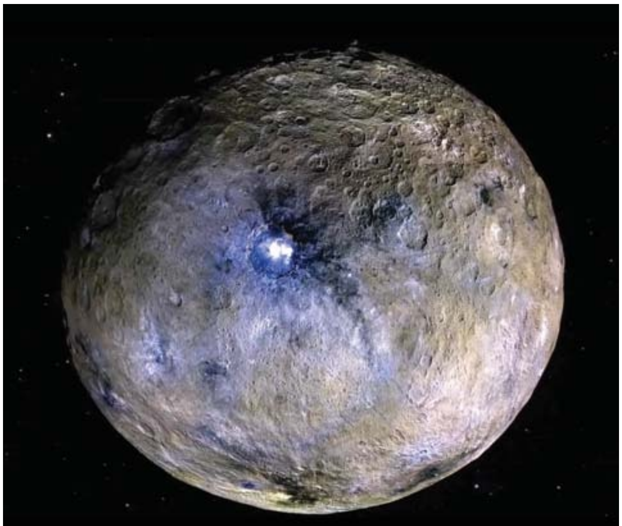
Those spectra have already revealed much more about the composition of Ceres. Most of the surface is a currently unidentified mixture of dark materials, but we now know that clay-like minerals known as *phyllosilicates* are ubiquitous on that faraway world. Many phyllosilicates are familiar on Earth, including mica. What makes their presence on Ceres particularly important is that they contain distinctive evidence of ammonia. The ammonia is bound up in minerals that form when water interacts with rock. This simple molecule, consisting of nitrogen and hydrogen, should have been common in the nebula of dust and gas from which the planets formed. But swirling around the young Sun, the material at Ceres' present location should have been too warm for ammonia to have condensed and been trapped in nascent planetesimals.

How then did it become so common on Ceres? It may be that Ceres formed much farther from the Sun, even beyond Saturn, where it was cool enough to incorporate ammonia, and the subsequent gravitational jostling of the planets pushed it to its current orbit. Another possibility is that Ceres formed close to where it is now but accreted material that originated farther away and moved in closer. That then raises the question of why so few other bodies in the vicinity display signs of ammonia. It also may be that our picture of the physical and chemical nature of the early solar system is wrong.

Carbonates, another group of minerals indicative of chemical reactions that take place in water, are common on Ceres as well. Indeed, the bright salt in Occator contains the highest concentration of carbonates known anywhere in the solar system except on Earth. And some of the minerals, such as serpentine and sodium carbonate, form only under pressure, as would occur beneath several kilometers of water.

Suppose the minerals were produced far underground and later forced to the surface by some geological process. Any mechanism for transporting the minerals from deep within Ceres should depend on the surface temperature and so should be different near the equator than near the poles, which on average diverge by more than 50K. (The surface temperature matters for what occurs inside because it affects the rate at which heat leaks out.) In that case, the distribution of minerals we see today should vary widely over the surface. But that is not what we see. Instead, the minerals show up nearly everywhere we look.

An alternative is that we may be looking at the floor of an ancient ocean! Heated by the radioactive elements incorporated when Ceres formed, the water would have been liquid, creating an ocean on the surface. But



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SOMETHING BLUE This false-color rendering of Ceres highlights differences in surface composition. The crater Occator and its spots appear just left of center.

exposed to the cold of space, the top would have frozen, encasing the dwarf planet in a shell of ice. Through a combination of blasting by impacts and sublimation, more than 100 km of ice could have been lost in the geologically brief span of 200 million years. As Ceres aged, it would have cooled, because radioactive elements in its interior decayed and provided less and less heat, making it more difficult for underground water to stay above the freezing point. But before it froze, the water would have provided a medium for complex chemical reactions, creating a rich inventory of minerals.

Although ice is certainly far more prevalent, could liquid water persist underground even today? Scientists don't know. The loss of heat over time depends not only on the specific supply of radioactive elements Ceres started with but also on how the heat moved. Salt, for example, conducts heat very poorly, so it could store thermal energy longer than rock. Also, the freezing point of water depends on what chemicals are dissolved in it. As one case in point, ammoniated salts make effective antifreeze. Scientists are using the extensive data from Dawn to refine mathematical models to gain insight into the interior conditions in the present and in the past.

Pockmark Pitfalls

It does not require mathematical models to see that Ceres has many craters. Or does it? To most people, the presence of craters on an ancient, airless world is not surprising. We know the solar system is replete with asteroids and comets that leave scars on the larger surfaces they strike.

But scientists did not expect to see *so many* craters on Ceres. In the darkness before Dawn, the reasoning was that if Ceres' crust were composed largely of ice (an assumption based principally on the dwarf planet's low density), then craters would disappear over geological time scales. As the ice flowed, albeit more slowly than glacial speeds, the surface would gradually relax, much as your skin relaxes after pressure from a fingernail is removed and the imprint eventually vanishes.

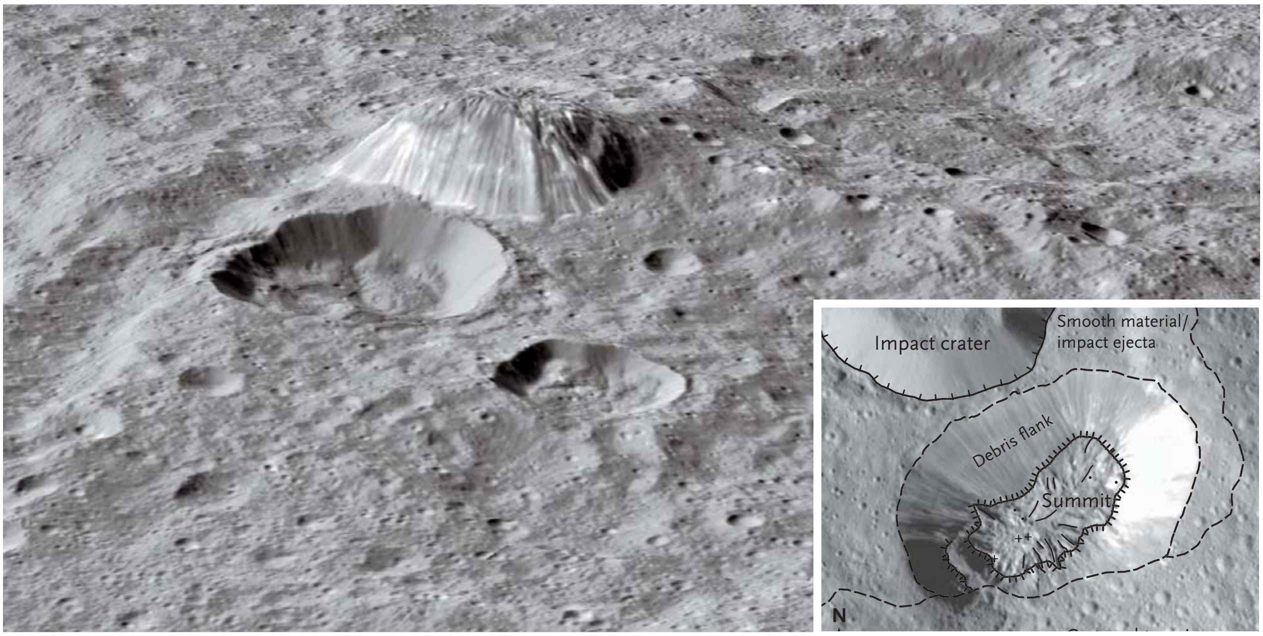
But Dawn has found areas on Ceres so heavily cratered, they are said to be saturated. That is, there are as many craters as it's possible for there to be. This may seem naïve. After all, no matter how many craters there are, if a small asteroid slams into Ceres, it will form at least one more. But a region saturated in craters has so many that any new impact is as likely to obliterate existing craters as it is to make new ones. Even in the rough-and-tumble main asteroid belt, it takes a long time to accumulate that many craters, so the process of relaxation on Ceres must be slower than expected. That is likely because of the abundance of salts and rock in that subsurface ice, making the combination stiffer than a more ice-rich layer would be.

But the mathematical models for how many craters should have formed at different sizes show there actually is a deficit of *large* ones. Based on what we found at Vesta, Ceres should have pockmarks up to sizes comparable with its diameter (roughly 900 km). Yet it has only 16 craters larger than 100 km, about 40% of the number expected. The two largest Cerean craters have diameters of 280 km (Kerwan) and 260 km (Yalode). In contrast, Dawn found a gigantic Vestan basin (Rheasilvia) more than 500 km in diameter and another (Veneneia) 400 km across overlapping at the south pole.

The absence of large Cerean craters could be the result of the loss of an exterior, icy shell or some internal processes that erase them. Scientists can use their

Dawn's Primary Mission Orbits Around Ceres

Mapping Orbit	Dates (2015)	Altitude in km (mi)	Resolution in meters (ft) per pixel	Resolution compared to Hubble
1	April 23–May 9	13,600 (8,400)	1,300 (4,200)	24×
2	June 6–30	4,400 (2,700)	410 (1,400)	73×
3	Aug 17–Oct 23	1,470 (915)	140 (450)	217×
4	Dec 16–Sept 2, 2016	385 (240)	35 (120)	830×



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LONELY MOUNTAIN Ceres is mostly a land of craters, but there are three major mountains. The most notable is Ahuna Mons, a strangely shaped protrusion that rises about 4,000 meters (13,000 feet) high. ***Inset:*** Ahuna Mons has a wide summit and steep sides covered in debris. It's likely a cryovolcanic dome, suggesting that Ceres' interior remained melted relatively recently.

knowledge now of the size and number of craters to help sharpen their geological picture of Ceres.

A Mountain of Data

Another striking sight is a tall mountain that rises precipitously from an otherwise unremarkable area. Ahuna Mons is the tallest mountain on Ceres, reaching about 4,000 m, or comparable to Mauna Kea. Despite its proximity to a prominent crater, it's unclear whether the impact had anything to do with the mountain's formation. Given the surrounding craters, the dome and its steep slopes are less than 250 million years old.

We now think that the dome built up from one or more gooey, cryovolcanic eruptions. Nearby impacts, or perhaps shock waves from a large planetary punch elsewhere on Ceres (such as the one that formed Kerwan) might have opened the fissures the cryomagma flowed through. Based on the world's composition, this goo was potentially a briny, mineral-tainted, water-ice mix. The summit would then be the brittle carapace that formed as the material cooled, and its fracturing might have produced the younger flank debris. Ahuna Mons's apparent youth suggests that some portion of the material within Ceres was in a melt phase in geologically recent times.

The presence of the various chemical ingredients, the retention of craters longer than originally predicted, and the profile of the interior density together show that Ceres has a crust-like exterior extending perhaps 70 to 190 km deep, or about 15% to 40% of the distance to the center. The much thicker interior must be softer and weaker. One scientist describes this world as being like crème brûlée.

Dawn's primary mission ended on June 30th, but NASA extended operations to continue investigating the fascinating world. Ongoing studies of Dawn's extensive measurements of Ceres' geology, geophysics, and chemistry will produce a great deal more new knowledge.

One of the signs of a successful scientific expedition is that it allows us to pose new questions that we could not have formulated before. By that measure, and by any other, Dawn is an outstanding success. And long, long after the mission ends, the astronomical discoveries the spacecraft enabled will continue to add to its legacy. After dawn, a new day arrives, and surely after Dawn a new mission sometime will arrive at Ceres to answer — and ask — still more questions. ✦

Orbit period	Equivalent distance of a soccer ball
15 days	3.2 meters (10 feet)
3.1 days	1.0 meter (3.4 feet)
19 hours	34 cm (14 inches)
5.4 hours	9.0 cm (3.5 inches)

Dawn Mission Director and Chief Engineer ***Marc D. Rayman*** *has been fascinated by astronomy and space exploration since the age of four. A few years later, he received his Ph.D. in physics and joined JPL. Among his most rewarding personal discoveries was* Sky & Telescope *when he was 12.*