Amazing Close-Ups of a Dwarf Planet p. 32

THE ESSENTIAL GUIDE TO ASTRONOMY

SKY & TELESCOPE

New Meteor Showers Discovered p. 20

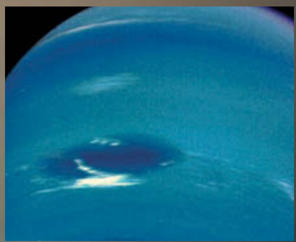
SEPTEMBER 2012

Extreme Weather

Storm Chasing in the Solar System p. 26

HOW TO
Tune Up Your Scope p. 72

Observe the Belly of the Swan p. 58



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Protoplanet Close-up

Jim Bell

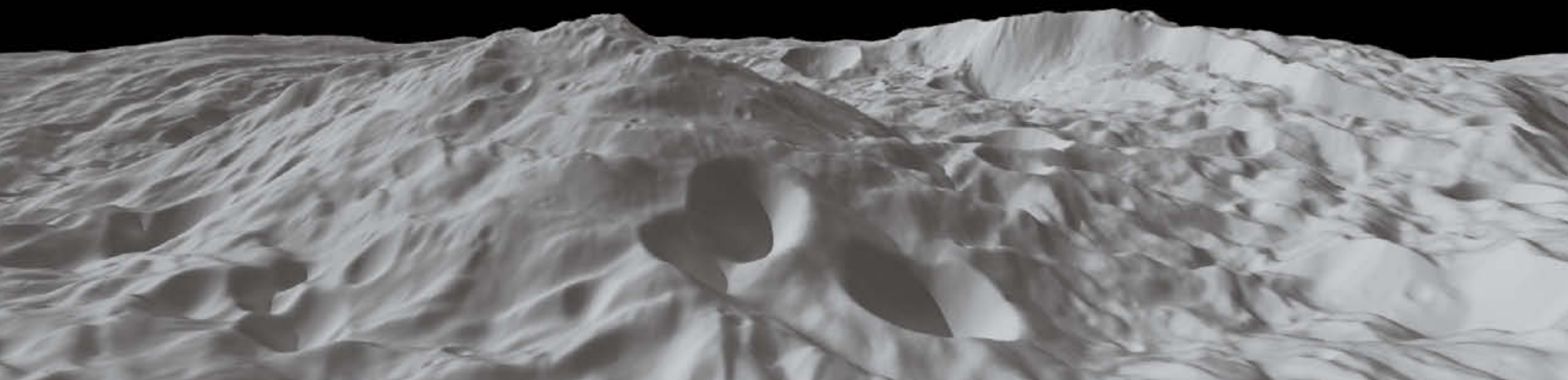
Dawn is revealing the history of Vesta, a unique world that is part asteroid and part planet.

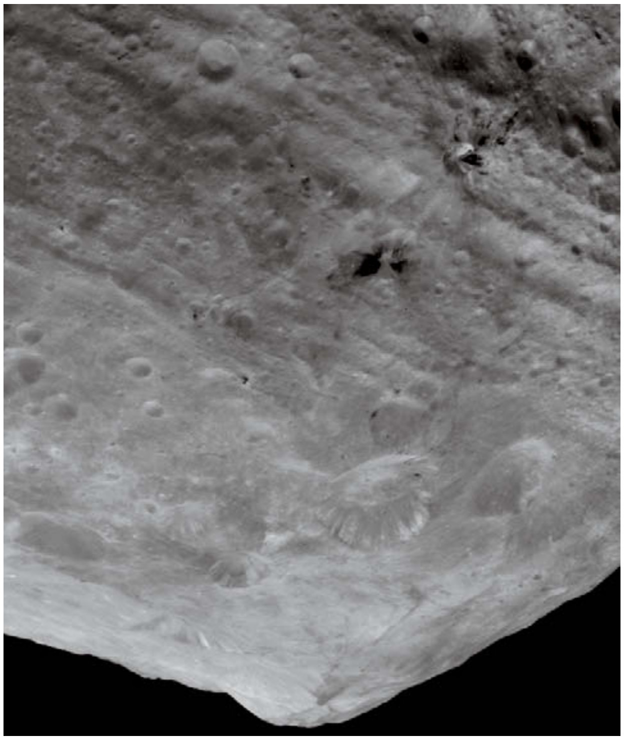
What is the recipe for building a planet? What kinds of building blocks are needed, and what forces hold them together or try to tear them apart? How does a planet's structure and composition change as it grows? What clues still preserved on planets or planetary fragments can help us understand their origins? These are the questions that NASA's Dawn mission was designed to answer.

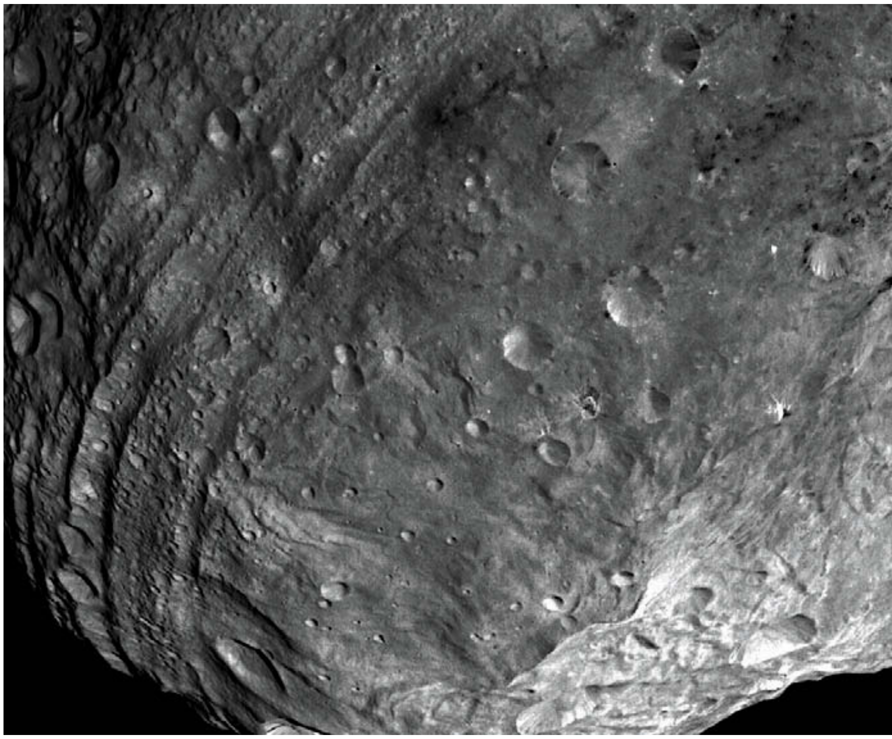
Dawn, the ninth mission in NASA's "faster, better, cheaper" Discovery series, is a spacecraft built to study two of the solar system's largest asteroids: Vesta and Ceres (*S&T:* November 2011, page 32). These two bodies alone represent a little over 40% of the mass of the main asteroid belt. Previous telescopic observations have hinted that rather than being primitive, unaltered objects like most smaller asteroids, Vesta and Ceres may be transitional protoplanets: part asteroid, part planet. If so, studying them up close could provide important clues about how planets such as Earth came to be.

Telescopic observations revealed Vesta to be dramatically different in color and surface mineral properties than any other large asteroid. Specifically, Vesta shows evidence of some of the kinds of basaltic minerals that we find in volcanic lava flows on Earth and other terrestrial planets. Scientists noticed that Vesta's infrared spectrum is remarkably similar to the spectra of a class of meteorites called the HEDs (Howardites, Eucrites, and Diogenites), ancient samples of which apparently started out as volcanic rocks within the crust or mantle of a large terrestrial planet or protoplanet and that were later transported to Earth by impacts. More recently, astronomers have found many smaller asteroids with Vesta-like spectral properties (Vestoids) traveling as families of small bodies in orbits related to Vesta's. Hubble Space Telescope imaging revealed an enormous hole at Vesta's south pole — as if a large chunk of the asteroid had been blasted off in a giant impact.

Dawn was launched in September 2007, cruised past Mars in 2009 for a gravitational assist, and settled into orbit around Vesta in July 2011. The spacecraft's ion-propulsion system, and a cautious, systematic mission-operations approach, have enabled the Dawn science team to study the asteroid's surface from successively lower orbits. A high-resolution color camera has obtained thousands of images down to resolutions of less than 100 meters, and a visible to near-infrared spectrometer has acquired millions of spectra of the surface down to resolutions smaller than 1 kilometer. These images and spectra have enabled the Dawn science team to make some exciting discoveries about Vesta's geology and mineralogy. Tracking of the spacecraft's orbit has enabled accurate measurements of Vesta's mass as well as detailed estimates of its interior structure.







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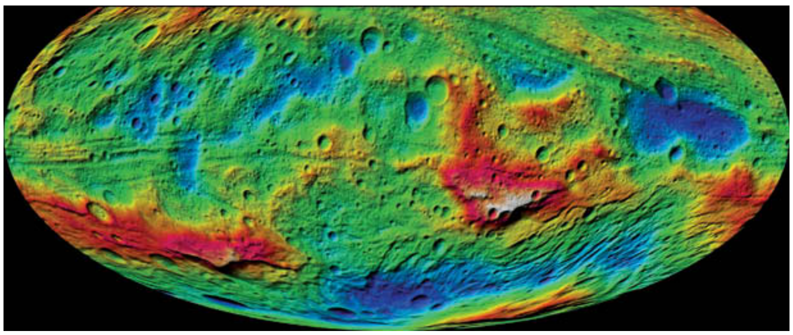
***Above left:* The south polar peak rises a whopping 15 km above the crater floor. *Above:* This image of Vesta's southern hemisphere highlights 10-km-wide equatorial grooves. The troughs are concentric to Vesta's two south polar impact basin and probably resulted from shock waves produced by the two giant collisions.**

Perhaps the most important finding is Dawn's discovery of not one but two enormous impact basins near Vesta's south pole. The largest, called Rheasilvia, is about 500 km (310 miles) across and nearly 20 km deep — more than enough volume to account for the HEDs and Vestoids. Rheasilvia has an enormous interior mound of rock nearly 200 km across and more than 20 km high, making it one of the solar system's highest mountains. We think it's the rebounded central peak created by the impact. Rheasilvia occurs on top of (and significantly overlapping) a slightly smaller (400-km-wide) basin called Veneneia. Using computer models of impact crater counts, scientists have estimated Rheasilvia's age as about 1 billion years and Veneneia's as about 2 billion years. The fact that they overlap near the south pole appears to be a cosmic coincidence. These two giant holes cause Vesta to appear distinctly flattened relative to a perfect sphere, as first noticed in HST images.

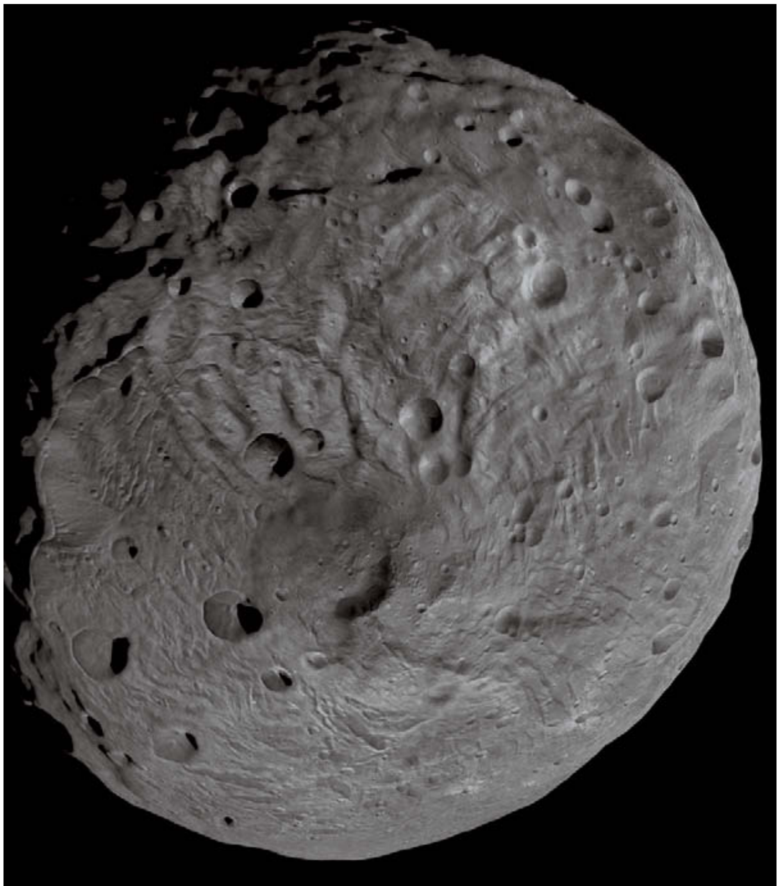
Indeed, impact craters dominate Vesta's shape and geology. Scientists have discovered five other basins larger than 150 km across, and thousands of smaller craters pockmark the surface. Vesta's surface is saturated with craters, meaning that the surface is so thoroughly covered by them that any new ones that form will wipe out enough old ones to keep the total number about the same. The two large south polar impacts appear to have reset the geology of the southern hemisphere, which has fewer craters overall than the part of the northern hemisphere imaged so far. All of these impacts have created a shallow, well-mixed layer of fine-grained impact debris — a *regolith* — overlying the asteroid's dense bedrock subsurface. Vesta's regolith is similar in some ways to the powdery, impact-created upper surfaces found on other asteroids such as 433 Eros, as well as on the Moon.

Dawn has also revealed lots of evidence for erosion, mostly in the form of landslides and slumps of material



NASA / JPL-CALTECH / R. JAUMANN (DLR) ET AL.

***Left:* This close-up of Vesta's south polar peak, with the asteroid's curvature removed, is based on a shape model. *Right*: A colorized terrain map of Vesta's surface illustrates the variety of topographical features. High areas are red and white, low ones are violet and blue. The equatorial grooves are easily visible.**

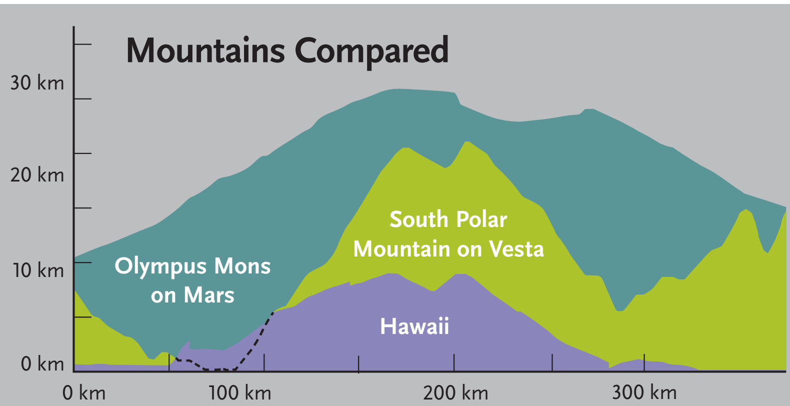


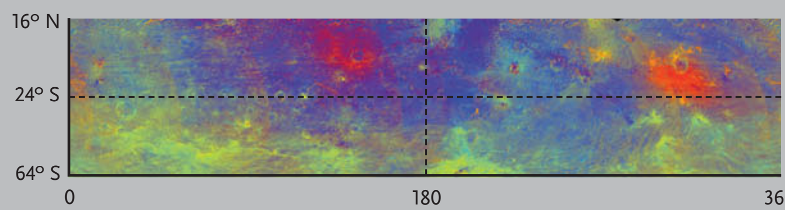
Rheasilvia, the larger south polar impact basin, dominates this view.

flowing down crater rims and walls due to Vesta's weak gravity (less than $^1/_{50}$th of Earth's gravity). Dawn has also detected a series of long, deep grooves and troughs that circle much of Vesta's equator. Although scientists are still debating the details of how these tectonic features formed, they are clearly concentric to the two large south polar basins, and so they must be related. Perhaps the shock waves generated by these enormous impacts helped to form these giant cracks.

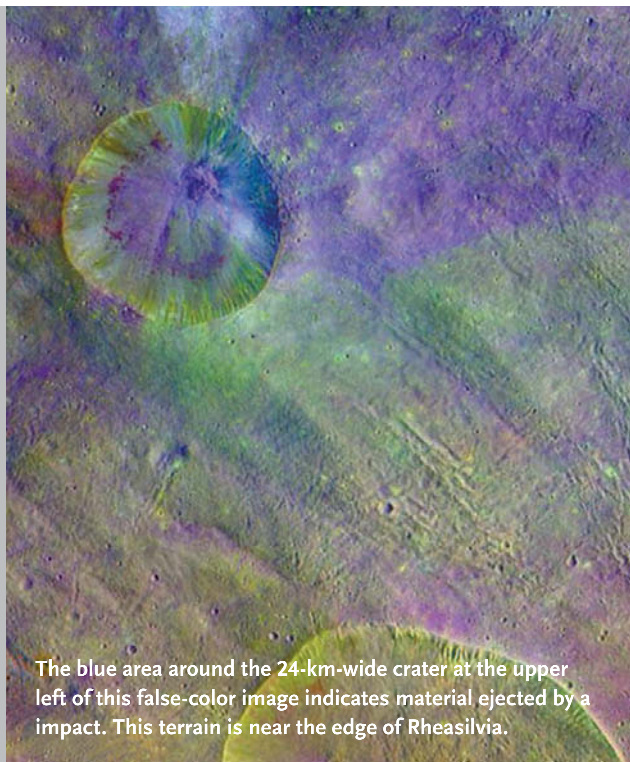
In addition to the geologic diversity, Vesta also exhibits the widest range of albedo (brightness), color, and infrared spectroscopic diversity of any asteroid yet encountered by a spacecraft. These variations indicate that Vesta is not a primitive world but instead that its surface materials have been processed by internal or external forces that can convert a planet's original inventory of rocks and minerals into other forms.

Indeed, a planet's mineral inventory provides information about the specific processes and environments that shaped that world. For Vesta, the composition consists of mixtures of basaltic volcanic minerals such as pyroxene — a common volcanic mineral on the terrestrial planets — as well as darker minerals whose types are more difficult to identify. The volcanic minerals match the compositions of the HED meteorites, which confirms the link between Vesta, the Vestoids, and this class of meteorite samples. The darker mineral phases could either be more iron-rich volcanic minerals, or perhaps more carbon-bearing materials from primitive (unprocessed) carbon-rich impactors that slammed into



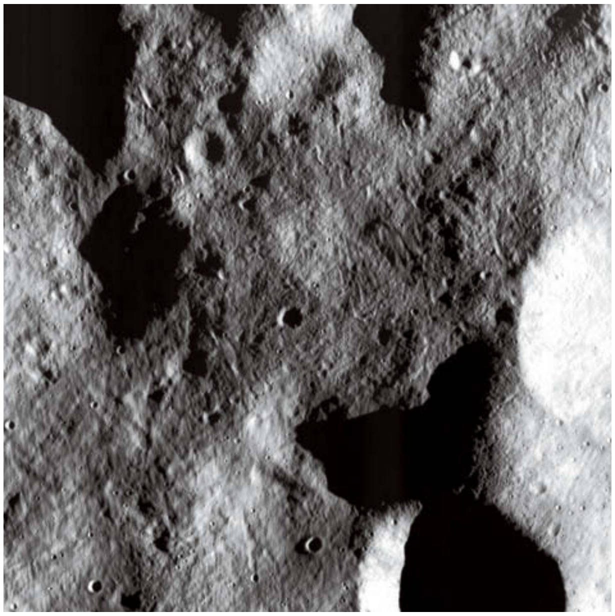


Top: The central peak in Rheasilvia rivals Mars's Olympus Mons as one of the solar system's highest mountains. *Above:* Green areas in this false-color map of Vesta indicate high volcanic-mineral content. Redder and bluer areas highlight regions with the strongest color differences.



The blue area around the 24-km-wide crater at the upper left of this false-color image indicates material ejected by a impact. This terrain is near the edge of Rheasilvia.

FAR LOWER LEFT: V. REDDY (MPI) ET AL.; FAR UPPER LEFT: C. T. RUSSELL (UCLA) ET AL.; NEAR LEFT: NASA / JPL-CALTECH, ET AL.



This image from Vesta's largely unexplored northern hemisphere shows its surface etched with subtle grooves, some of which run for dozens of kilometers but are less than 1 km wide. Shifting regolith on Vesta's surface may be responsible for the grooves.

Vesta over time. If it's the latter, these may be the kinds of organic materials that helped seed the ingredients for life on Earth when delivered here by impacts.

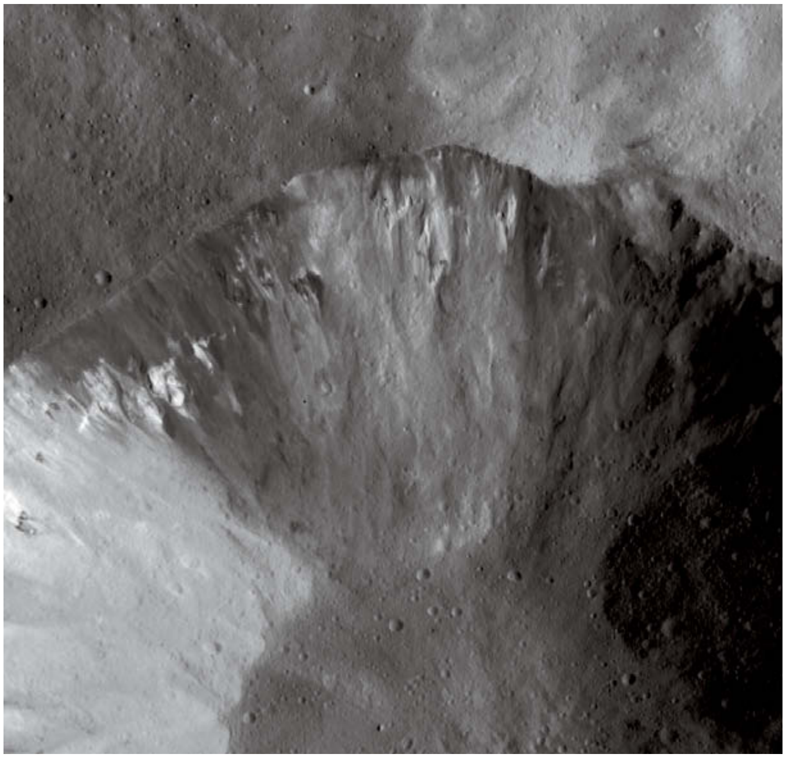
Somewhat surprisingly given Vesta's mineral composition, Dawn has seen little or no evidence for lava flows, dikes, cones, domes, or other volcanic structures. Maybe these features once existed on Vesta, but they have since been destroyed by the onslaught of impact cratering. Or perhaps Vesta's volcanism has always been hidden below the surface.

Looking at the bigger picture, the distribution of surface and impact-excavated minerals indicates that Vesta is a *differentiated* world. That is, the asteroid must have been at least partially melted early in its history, perhaps even with a melted ocean of magma floating at the surface. This enabled heavier iron- and nickel-bearing materials to sink and lighter silica- and oxygen-bearing materials to rise, segregating the interior into a core, mantle, and crust. Vesta's initial melting probably came from the combined heat of radioactive elements within the interior and the heat energy of innumerable impacts.

Differentiation into a core, mantle, and crust, and evidence for interior volcanic processes, are typical hallmarks of a terrestrial planet. Indeed, Dawn's measurements of Vesta's mass, combined with an estimate of the asteroid's volume from stereo imaging data, indicate that it has a high rocky and metallic density of about 3.4 grams/cm^3, comparable to the densities of the Moon and Mars. By some definitions, then, Vesta should be considered a planet, albeit a small one.

Some scientists think that Vesta may in fact be a protoplanet. In other words, Vesta may be the preserved remnant of a transitional class of planetary objects — it's no longer a primitive asteroid but it's not quite a classical terrestrial planet either. The world's meteorite collections reveal that we have samples from perhaps 100 or more such transitional protoplanets, including the parent body of the HEDs. Vesta is almost certainly that parent body, but it's the only object we know of in the solar system for which we can make that kind of claim. Vesta may thus be the last of its kind, a rare survivor of the violent era of planet formation.

Dawn's mission at Vesta will continue through most of the summer of 2012. The science team will collect images and other data of Vesta's far northern hemisphere, which has been in winter darkness for most of the mission so far. Scientists are only now analyzing the compositional results from the gamma-ray and neutron spectrometer, since it took such a long time to build up the required signal levels during the mission's recent low-orbital-altitude phase. Will there be additional geological or mineralogical surprises in Vesta's more ancient northern hemisphere? Will the gamma-ray or neutron data reveal the presence of hydrogen-bearing materials (hydrated minerals or even ices) or other volatiles in the subsurface?



From an altitude of 272 km, Dawn examined a portion of this 40-km-wide crater that's located a few degrees south of the equator. The crater's sharp rim indicates a fairly recent impact, and its interior walls feature a variety of bright outcroppings.

According to the current plan, in late August 2012, the spacecraft will be gently guided out of Vesta's orbit and on to its next encounter: a February 2015 orbital rendezvous with Ceres, the solar system's largest asteroid. Based on telescopic observations, Ceres is very different from Vesta, with a lower density and likely a more icy composition. What surprises await us there? Will Ceres prove to be a surviving protoplanet like Vesta, or something entirely different? I can't wait to find out! ✦

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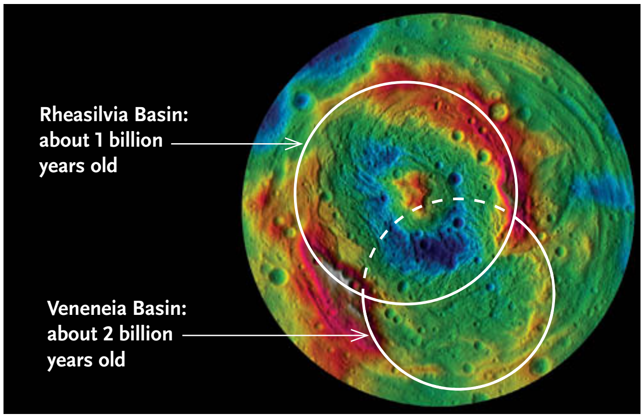
*Contributing editor **Jim Bell** is a professor of astronomy and planetary science at Arizona State University. He was involved in the NEAR-Shoemaker mission to asteroid 433 Eros and is the lead scientist for the Mars Exploration Rover Pancam instruments. When not studying planetary surfaces, he roots for the Boston Red Sox and paddles Hawaiian outrigger canoes.*



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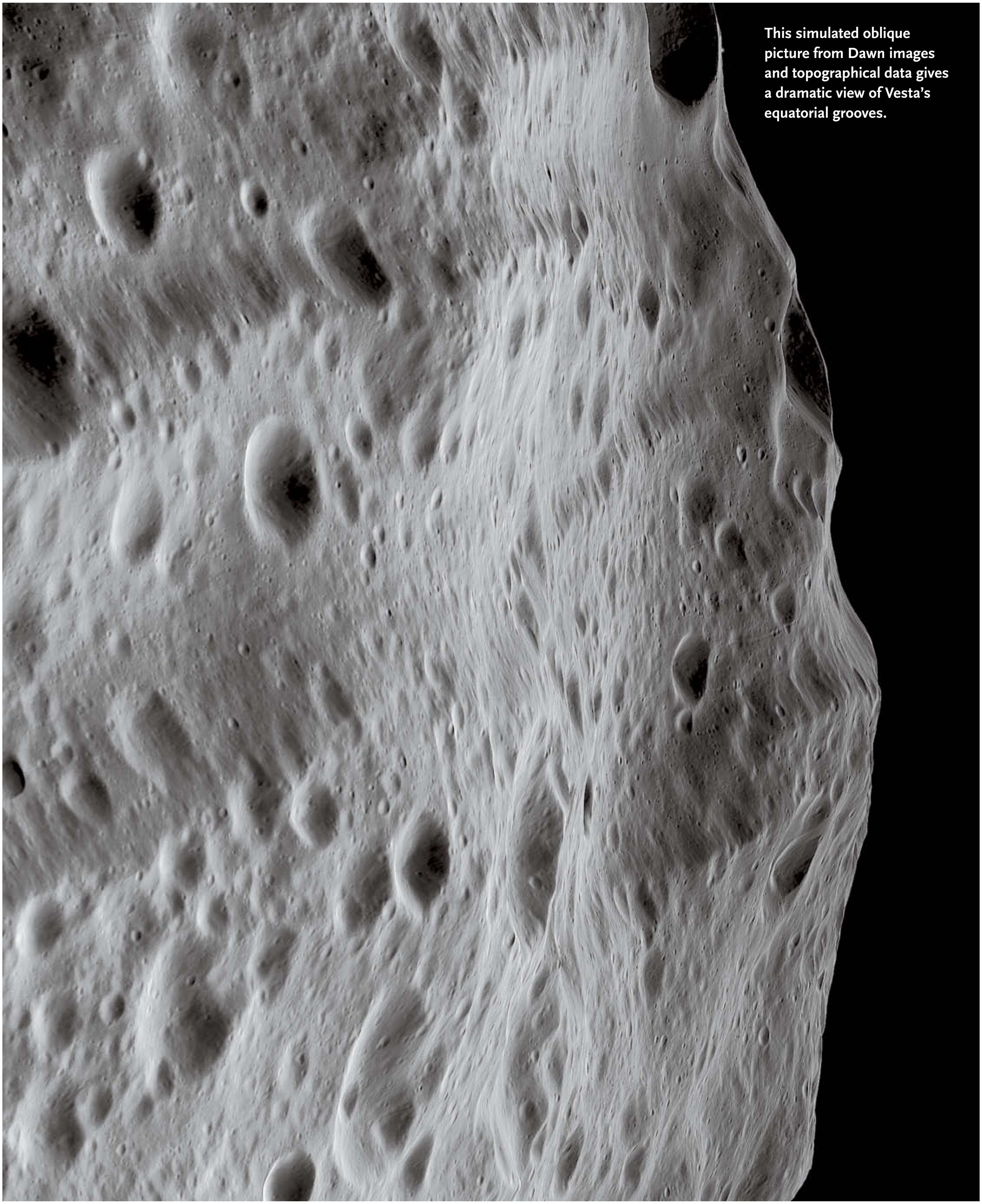
By counting craters, scientists can estimate the ages of the two giant impact basins around Vesta's south pole. As this false-color map shows, the two basins overlap — a cosmic coincidence.

Vesta's equatorial grooves are easily seen in this high-altitude image. The south polar peak dominates the bottom. The north pole has been hidden in darkness for most of Dawn's mission so far. The two large south polar impacts led to Vesta's aspherical shape.



This simulated oblique picture from Dawn images and topographical data gives a dramatic view of Vesta's equatorial grooves.